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Developing biology teachers' pedagogical content knowledge through learning study: the case of teaching human evolution

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ABSTRACT

This work explores how pedagogical content knowledge (PCK) on evolution was modified by two biology teachers who participated in a professional development programme (PDP) that included a subsequent follow-up in the classroom. The PDP spanned a semester and included activities such as content updates, collaborative lesson planning, and the presentation of planned lessons. In the follow-up part, the lessons were videotaped and analysed, identifying strategies, activities, and conditions based on student learning about the theory of evolution. Data were collected in the first round with an interview before the training process, identifying these teachers' initial content representation (CoRe) for evolution. Then, a group interview was conducted after the lessons, and, finally, an interview of stimulated recall with each teacher was conducted regarding the subject taught to allow teachers to reflect on their practice (final CoRe). This information was analysed by the teachers and the researchers, reflecting on the components of the PCK, possible changes, and the rationale behind their actions. The results show that teachers changed their beliefs and knowledge about the best methods and strategies to teach evolution, and about students' learning obstacles and misconceptions on evolution. They realised how a review of their own practices promotes this transformation.

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Pedagogical content knowledge; learning study; teaching human evolution; nature of science; professional development programme

Introduction

Different studies have described the teacher as a determining factor in student learning (Abell, 2007; van Driel, Berry, & Meirink, 2014; Hattie, 2003). A great number of other works have focused on questions related to what professional knowledge is necessary for education or what type of knowledge is the most important in pedagogical practice (Abell, 2007). According to this, teaching becomes a complex task (Loughran, Berry, & Mulhall, 2012), even more so for science education, in which teachers have the objectives of promoting the development of the sciences, scientific literacy, social justice, and a critical approach, among others (Reiss, 2007).

For more than three decades, pedagogical content knowledge (PCK) has been recognised as not only one of the most important components of professional knowledge but

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also one of the most complicated to understand (van Driel et al., 2014; Gess-Newsome, 2015; Shulman, 2015). Shulman (1986, 1987) defines PCK as follows:

> It (PCK) represents the blending of content and pedagogy into an understanding of how a particular topics, problems or issues are organized, represented and adapted to the diverse interests and abilities of learners and presented for instruction. (Shulman, 1987, p. 8)

After this first proposal, many other researchers have modified and reinterpreted PCK (Gess-Newsome, 2015; Grossman, 1990; Lederman & Gess-Newsome, 1992; Magnusson, Krajcik, & Borko, 1999; Park & Oliver, 2008). Moreover, the representation or characterisation of PCK has been a complex task, despite being a widely accepted construct in educational research (Abell, 2008; Loughran, Mulhall, & Berry, 2004; Vergara & Cofré, 2014). For some authors, PCK consists of the relationship of what the teacher knows about the content, what he/she knows about what to teach about that content, what he/she knows about how to teach it, and what he/she knows about why to teach it (Loughran et al., 2004). This relationship between the teacher's decisions and knowledge hinders its capture, and as portraying it becomes so complex, it is also difficult to know how to develop it and, afterward, to know how to evaluate it (Park & Oliver, 2008).

In response to this challenge, diverse methods for capturing, representing, or evaluating PCK have been proposed (e.g. Abell, 2007; van Driel et al., 2014; Gess-Newsome, 2015; Henze & van Driel, 2015; Loughran et al., 2012; Park & Oliver, 2008; Schmelzing et al., 2013; Smith & Banilower, 2015). Among them, Loughran and colleagues (Hume & Berry, 2011; Loughran et al., 2012; Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001) have developed a qualitative method to capture a science teacher's PCK that comprises two important elements: the Content Representation (CoRe) and the Pedagogical and Professional-experience Repertoire (PaP-eR). According to these authors, the PaP-eR illustrates the reasons and foundation of the teacher's knowledge, which emerge through the CoRe (Loughran et al., 2001). In other words, in this view, it is recognised that there are at least two components of PCK: *declarative* PCK and *procedural* PCK (Schmelzing et al., 2013). Other authors have described this separation as PCK *on action* and PCK *in action* (Park & Oliver, 2008) or simply *to know what* versus *to know how* (Baumert et al., 2010).

The representation of PCK involves a greater understanding of this knowledge and its influence on teachers' practices (Magnusson et al., 1999). For teachers, being aware of their PCK involves understanding how they can promote their students' learning of specific content (Nilsson, 2014). Given the above, it is necessary to transform the training opportunities of science teachers towards the consideration and development of PCK, both at the level of initial training (Lederman & Lederman, 2015) and in continuing education (Nilsson, 2014).

In this latter training context, professional development programmes (PDPs) can make a difference in how teachers develop their PCK (Nilsson, 2014). Traditionally, these instances of continuing education are vertical, where a university-based expert passes on knowledge to teachers without considering their expertise in the classroom. However, opportunities to develop PCK should be created by considering 'professional learning' in which the work is with and for teachers (Nilsson, 2014).

In this context, this study had the objective of understanding how the PCK was developed for one of the most important and complex topics in biology education: the theory of evolution (TE). For that purpose, two biology teachers who participated in a PDP were studied in-depth, which included both training at the university on the TE and its teaching, in addition to a follow-up in school where the teachers applied some of what they had learned. Specifically, we were interested in understanding how the teachers' PCK was modified and, furthermore, in proposing a method to capture a PCK that combines one of the most utilised methodologies in the literature (CoRe and PaP-eR) with one of the most utilised PCK theoretical models (Magnusson et al., 1999). The questions that guided this research were as follows: (1) How do two biology teachers develop elements of PCK for evolution through their participation in a PDP that includes a follow-up in their classroom? (2) What elements of the biology teachers' PCK for evolution changed due to the PDP?, and (3) According to the teachers, what elements of this PDP were responsible for the modifications to their PCK for evolution?

Capturing PCK

Studying PCK is important because it is knowledge particular to each teacher (Shulman, 2015). Different authors state that, of the teacher's types of knowledge, the most complex is PCK (Loughran et al., 2001, 2004, 2012; Shulman, 1987). This complexity means that it behoves us to resolve to understand how the PCK is formed, and what elements it includes. Magnusson et al. (1999), focusing on science PCK, propose five PCK components and their definitions: (1) orientation towards teaching science; (2) knowledge of science curriculum; (3) knowledge of students' understanding of science; (4) knowledge of assessment in science; and (5) knowledge of instructional strategies.

As Baxter and Lederman have noted, evaluation of PCK is a complex task that requires a combination of approaches to improve the quality of information on what teachers know and do and the reasons they perform their actions. In this sense, to study and evaluate PCK development, it is advisable to collect data from multiple sources, including knowledge assessment tools based on questionnaires with closed- and open-ended questions (Baumert et al., 2010; Schmelzing et al., 2013), tasks or written reflections (Loughran et al., 2004; Park & Oliver, 2008; Rozenszajn & Yarden, 2014), observations of lessons conducted by teachers in training or working (Loughran et al., 2004), semi-structured interviews (Park & Oliver, 2008; Rozenszajn & Yarden, 2014), 'stimulated recall' about lessons conducted (Loughran et al., 2004), lesson planning (Rozenszajn & Yarden, 2014), and field notes (Park & Oliver, 2008).

Two of the most utilised proposals for this purpose are the CoRe (Content Representation) and PaP-eR (Pedagogical and Professional-experience Repertoire) tools developed by Loughran, Milroy et al. (2001) and Loughran, Mulhall et al. (2004). These were developed after several years of working with science teachers with a great deal of experience. These tools have been widely used to describe and document the PCK of primary and secondary school teachers, especially science teachers (Abell, 2008; Loughran et al., 2001, 2004; Nilsson & Loughran, 2012; Padilla, Ponce de León, Rembado, & Garritz, 2008). The CoRe corresponds to a proposal by these authors to generate discussion among teachers and therefore have a common basis for a conversation that would show how teachers represent content to make it understandable to others. Moreover, the PaP-eR serves to illustrate how knowledge documented in the CoRe may be reflected in the act of teaching (Loughran et al., 2004). Each PaP-eR is the result of the teacher's reflection related to a specific aspect of PCK and his/her practice. It can emerge through an interview of 'stimulated recall', in which there is a confrontation of knowledge documented in the CoRe through the analysis of videotaped teaching situations related to the content addressed by the teacher, or it can also arise from written individual reflections by the teacher about a particular class (Loughran et al., 2004, 2012). Therefore, the CoRe and the PaP-eR jointly offer an opportunity to understand the decisions behind the classroom practice of teachers so that the content is understandable for their students (Loughran et al., 2004), which means that they serve to characterise both declarative PCK (CoRe) and procedural PCK (PaP-eR).

Nonetheless, there are also limitations in terms of the number of teachers who can be studied with this and other qualitative methodologies. For this reason, other authors have preferred to develop quantitative tools to measure PCK on biology (Schmelzing et al., 2013) or mathematics topics (Baumert et al., 2010). Some intermediate proposals have utilised a pictorial representation of the interactions of five PCK components, that is, 'PCK Maps' (Park & Chen, 2012), or rubrics, with which the procedural PCK is measured, evaluating the four subcomponents that form it (Park & Oliver, 2008). The rubric can have different levels of achievement that range from limited to advanced. These rubrics can be applied to different types of data: planning, interviews, and classroom observation. The final value of PCK can be generated through three measures: the sum of scores, the average, and the highest value obtained.

Teaching and understanding evolution

There is abundant evidence that many science teachers (including biology teachers) have problems both in understanding the TE (especially natural selection) and in accepting it as valid scientific knowledge (e.g. Cofré, Jiménez, Santibáñez, & Vergara, 2016; Ha, Baldwin, & Nehm, 2015; Kim & Nehm, 2011; Nunez, Pringle, & Showalter, 2012). For example, Kim and Nehm (2011) report that the acceptance of the TE by biology teachers reaches low levels in the United States and Turkey, where it does not exceed 60%, whereas in European countries, there are lower levels of rejection by biology teachers, but even these remain close to 20% in Germany, Austria, Switzerland, and England. Some characteristics of teachers that have been associated with a lack of acceptance and understanding of evolutionary theory are: a weak preparation in the evolutionary content in their initial training; a poor understanding of the nature of science (NOS) (including the common misconceptions that a theory is just a guess that needs to be transformed into a law to become valid scientific knowledge); their own creationist religious beliefs; and their inability to withstand community pressures to teach non-scientific alternatives to evolution (e.g. Glade & Goldstons, 2015; Ha et al., 2015; Kim & Nehm, 2011; Lombrozo, Thanukos, & Weisberg, 2008; Sickel & Friedrichsen, 2013).

Despite this conclusion, there are few examples of studies on PDP that focus on improving the knowledge and acceptance of evolution by working teachers (e.g. Crawford, Zembal-Saul, Munsford, & Friedrichsen, 2005; Ha et al., 2015). In one of the more recent works, Ha et al. (2015) show that a brief PDP (10 intensive days) based on principles derived from research can have a positive and lasting impact on improving teachers' knowledge and acceptance of the TE. However, the study of teachers' abilities to teach these contents and evaluate and manage alternative ideas that students have, meaning

PCK on evolution, has been almost unexplored. One of the few studies conducted in Germany to evaluate the PCK on evolution of working teachers showed that they believe that students' alternative ideas on evolution can be replaced by correct scientific knowledge. Furthermore, teachers in that study did not perform teaching strategies aimed at working with the misconceptions that students uphold (van Dijk, 2009). Therefore, the need to investigate the impact of PDP on the development of teachers' PCK on evolution remains.

PDP based on PCK

In general, the work of teaching and, in particular, education is not theorised by teachers because they often already have too much content to teach. For the majority of teachers, theorising does not necessarily help solve the daily problems that education involves; therefore, they do not have much interest in articulating the relationship of their practice with academic knowledge (Loughran et al., 2001, 2004; Nilsson, 2014). On the other hand, teachers typically share the experiences that they have with teaching but not in theoretical terms, which is related to having little practice explaining the basis of their decisions about what they do in class in academic language (Loughran et al., 2001).

Finding the balance between theory and practice is important for building knowledge, and, with it, an educational change can be achieved. One approach to this type of mix would be 'learning study' (Nilsson, 2014) as a type of professional development with the rationale that the science teacher is considered as an apprentice, in this case of his/her own learning (Loughran, 2014a). Training opportunities should revolve around how teachers can develop their PCK and be aware of it (Nilsson, 2014). As stated above, PCK is dynamic and changes according to different actions. Regarding how to develop PCK, Shulman (1987) proposes that the main action can be achieved by teachers themselves through what is called the 'wisdom of practice itself', in which teachers make changes to the components of PCK as a result of their own reflection. The same author defines three other forms of PCK development: (1) scholarship in content disciplines; (2) materials and settings of the institutionalised educational process; and (3) research on schooling social organisations, human learning, teaching and development, and the other social and cultural phenomena that affect what teachers can do.

Training opportunities related to PCK development should ensure the possibility of sharing practice and learning from experience, similar to what has been described in the development of 'professional learning' (Loughran, 2014b; Nilsson, 2014). These instances involve building trust among teachers to be able to express all opinions regarding practice about what is done well and what is not (González-Weil et al., 2014). As such, opportunities for professional development, by this logic, would contribute to the modification of PCK by teachers, and they, in turn, would be aware of it.

Context of the study

In Chile, the curriculum is prescribed by the government for all kinds of schools. The required amount of schooling is 12 years of primary and secondary education. Secondary biology teacher programmes include extensive education in scientific subjects (typically more than 15 courses in four years) but limited training in science instruction (typically only two courses) (Cofré et al., 2010, 2015). Some of these programmes include one content course of evolution, but some of the programmes include only one course of evolution and genetics, and a few programmes even did not include the subject of evolution at all (Cofré, Vergara, Santibáñez, & Jiménez, 2013).

In Chile, as recently as 1991, the TE was integrated into the science curriculum in the elective plan of grades eight and eleven, which reflects the low coverage of this topic at the national level. However, there are different research groups that contribute to books that could strengthen students' understanding of the TE. Currently, the TE is taught in the eighth and eleventh grades of school. Regarding the situation of evolution understanding in Chile, a study conducted by Cofré et al. (2013) with university students reveals that their acceptance of the TE reached 74%, but their understanding of the mechanism of natural selection is very poor.

The study of PCK in Chile is a very recent development, and in science education, in particular, is almost absent (Vergara & Cofré, 2014). There are only two studies on mathematics teachers' PCK that attempted to understand the relationship between teachers' PCK and students' learning. The first study related teachers' PCK to students' understanding of fractions in mathematics, finding that a teacher's PCK is significantly associated with the learning and grades of the students (Olfos, Goldrine, & Estrella, 2014). The other study explored the evaluation of a PCK component related to the teacher's knowledge about how his/her students learn mathematics, resulting in a re-evaluation of the teacher's knowledge about how to teach the content (Varas, Lacourly, López, & Giaconi, 2012).

Methodology

This research is qualitative in nature, with a multiple case design to understand the modification of PCK on human evolution by two biology teachers who participated in a PDP and its follow-up. The 'capture' of PCK is a complex problem to address; thus, in this research, an interpretive approach was employed to accomplish the study's objectives.

The relationship among the research questions, instruments, and stages of the PDP is shown in Table 1.

Participants

This study included two in-service secondary biology teachers who participated voluntarily in the first stage of a PDP. These biology teachers were chosen from a total group of 10

Table 1. Relationship among: research questions, instruments and PDP.

Research questions	Instruments	PDP
(1) How do two biology teachers develop elements of PCK for evolution through their participation in a PDP that includes a follow-up in their classroom?	Interview 1 (Individual initial Content Representation: CoRe) Interview 3 (Individual final Content Representation: CoRe)	After the intensive course in January 2014 After analysis of the recorded lessons
(2) What elements of the biology teachers' PCK for evolution changed due to the PDP?	Interview 3 (Individual final Content Representation: CoRe)	After analysis of the recorded lessons
(3) According to the teachers, what elements of this PDP were responsible for the modifications to their PCK for evolution?	Interview 2 (group)	After follow-up in their classrooms

biology teachers that attended to the PDP (see the next section for a description of the PDP). They were chosen because they were willing to participate in a second stage of the programme, as well as because they had to teach evolution in the following term in high school (not all biology teachers that attended the first stage of the PDP had to teach evolution immediately at the beginning of the school year).

The two biology teachers studied in the same biology teacher-training programme at the same university but have different years of experience in schools in Valparaíso (see Table 2). Both teachers showed a poor understanding of the NOS and of evolution at the beginning of the PDP. However, at the end of the first part of the PDP (at the university), both teachers reached a very good level of knowledge regarding evolution, as well as the NOS, which was determined by valid and reliable instruments.

The students of these teachers were in their eleventh year of school (secondary education), in its elective branch (16 years of age on average). Because they were minors, their parents signed an informed consent form to allow recording of the conducted lessons.

Description of the PDP

During 2014, two biology teachers and two researchers (the authors) worked together on a PDP belonging to a publically funded research project. The PDP had the main objective of updating teachers on the content of evolution and the NOS and its teaching and, in turn, accompanying them in conducting lessons in which they addressed this topic with their students.

The PDP included a first stage of content updates about the topic of evolution during the first week of January 2014 (an intensive course consisting of 30 chronological hours). Like most of the teachers who attended this PDP, at the beginning Peter and Annie acknowledged not having a thorough knowledge about evolution and also recognised not having teaching strategies on the issue. The first course included a review of two central theories of evolution, natural selection, and common ancestry, and how these theories include facts, hypotheses and laws (such as the law of exponential growth) (Mayr, 2001). We incorporated aspects of palaeontology of mammals from Chile, hominin phylogeny, and examples of human evolution and natural selection in everyday life. The course also included teaching about the NOS in an explicit and reflective way (Cofré et al., 2016) and discussion about the relationship between NOS and the acceptance of

Table 2. Teachers' profiles at the beginning of the second stage of the PDP. The level of knowledge of teachers was determined by the application of valid and reliable instruments described in the literature.

Characteristics	Annie	Peter
Age	36	29
Years of experience	10	4
Current experience in the school	10	3
Type of school	Private	Semi-private
Role at school	Head of the science department	Head of the science department and curriculum coordinator
Knowledge about evolution	Good	Excellent
Knowledge about the NOS	Good	Excellent

evolutionary theory. Finally, themes of teaching and understanding evolution were also included, such as the importance of NOS in comprehending the TE, evolution misconceptions, and the most common obstacles when teaching this topic. Discussions were about inquiry-based strategies for teaching evolution, the inclusion of topics of human context in instruction, and reflection on the way in which research in evolution is undertaken. Afterwards, the two teachers participating in this research continued in a second stage of the PDP, which included lessons planning and follow-up in their classrooms. This second stage, which occurred between April and July 2014, began with a task in which the two teachers collaboratively planned lessons on human evolution that they would conduct during the first school semester of 2014. In this planning, the teachers made decisions about the curricular content that they would address and the teaching strategies and activities that they would perform. They also created and modified materials such as guides and presentations. During this process, the researchers attended half of the planning meetings (three out of six), which were audio-recorded. In these, the researchers fulfilled the role of accompanying the process, providing materials, and responding to the questions that the teachers presented about teaching human evolution, given that the teachers wanted to include some of the activities performed in the PDP held in January 2014.

The lessons carried out by the teachers at their schools were recorded by one of the two researchers with a video camera. The researchers video-recorded six lessons per teacher between the months of June and July 2014. The teachers, together with the researchers, decided to conduct lessons about human evolution, relating the content to aspects of the NOS. Consequently, the two initial lessons included activities where some aspects of NOS were explicitly taught, and the four subsequent lessons focused on the teaching of human evolution, highlighting the way in which the knowledge had been generated.

Data sources

The data collection presented below corresponds only to the second stage of the PDP. At the beginning of this second stage, a semi-structured interview with each teacher was conducted (Interview 1), asking for the representation of content that they possessed on the TE. The adopted format for this interview was a modification of the tool developed by Loughran et al. (2004) known as the CoRe. The questions that directed this initial interview are summarised in Table 3 and should be understood as an orientation. When necessary, additional questions were incorporated to go more in-depth about certain aspects or to gain more information when a lack of clarity remained (Hernández, Fernández, & Baptista, 2010).

As stated above, six lessons per teacher were recorded, and after those recordings, a second interview (Interview 2) was conducted, which was also semi-structured but in a group context. Its objective was to understand the impact of the PDP (especially from the second stage) and the experience of collaborative work, in addition to examining the elements that the teachers believed they had changed in their PCK after completing the lessons, considering their statements in the first individual interview. Finally, a third (individual) interview (Interview 3) was conducted with each teacher of stimulated recall (stimulated recall interviews or SRIs), where some moments from the filming of lessons were reviewed together with the researcher. The use of this technique encouraged and motivated the teachers' reflective practices (Nilsson, 2014), with each teacher being

Table 3. Relationship between CoRe elements and PCK components according to Magnusson model.

CoRe (Loughran et al., 2004)	Components of PCK (Magnusson et al., 1999)
What is the central concept or most important idea you hope the students learn about evolution?	Knowledge of science curriculum
Why it is important for students to know about evolution?	Knowledge of students' understanding of science
What else do you know about evolution (that you do not intend students to know yet)?	Knowledge of students' understanding of science
Which are the difficulties or limitations connected with teaching evolution?	Knowledge of students' understanding of science Knowledge of science curriculum
Which are the misconceptions or other students' features that most influence learning about evolution?	Knowledge of students' understanding of science
What other factors influence your approach to teaching evolution?	Knowledge of students' understanding of science
What strategies do you know are effective for teaching evolution? Why?	Knowledge of instructional strategies
Which are the specific ways of assessing studentś understanding of evolution?	Knowledge of assessment in science

interviewed on his/her behaviour and actions in these lessons (Dempsey, 2010). These interviews were designed through a comparison of answers from interview 1 and excerpts from selected lessons by referencing some aspect noted in the first interview. Emphasis was placed on the aspects of PCK in which some change was observed to obtain the baseline of the teachers.

The first and third interviews relate to the first and second research questions and these interviews were individual because what they were intended to reveal is how the PCK in each teacher changed, specifically with regard to what they knew about teaching evolution. However, to understand the impact of the PDP in general, a group interview was conducted to obtain the overall perception of the programme. The third interview related to the second research question, but was at the end because it entailed watching the entire set of lessons for each teacher.

Qualitative data analysis

The methodology of this study was to link and relate tools developed by Loughran et al. (2012) to describe and capture the PCK of teachers (CoRe and PaP-eR) with the model by Magnusson et al. (1999), which recognises five PCK components. In this research, just four of the five PCK components of Magnusson et al. (1999) were considered. The orientations towards teaching science' component was not considered because it 'refers to teachers' knowledge and beliefs about the purposes and goals of teaching science at a particular grade level' (Magnusson et al., 1999, p. 97) and in this case the focus was specifically to understand teaching about the TE as content (see Table 3). Therefore, in this proposal, one could identify differences in the central ideas, misconceptions, strategies and limitations, and methods of evaluating teaching, which teachers recognised before and after conducting lessons (Magnusson et al., 1999). The analysis of the two individual interviews per teacher (four in total) and the group interview was performed utilising the software package Atlas.ti 6.2.

In interview 1, an initial image of each teacher's CoRe elements was constructed, and in interview 3, a final image of these same elements was constructed. The presented images are the result of the content analysis of interviews 1 and 3 with each teacher. In the first analysis, the information was coded; subsequently, the codes were grouped into broader categories corresponding to the PCK components of Magnusson et al. (1999). To establish the validity of the coding, only those responses that were coded in the same way by the two authors were accepted as valid data for analysis. Finally, each code was linked with an arrow to different codes according to the teacher's responses, regardless of how often the linkage was made. Afterwards, the final image was compared with the initial image, emphasising the recognition of new codes associated with the studied PCK components declared by the teachers. Finally, the PaP-eR was created, which, according to Loughran et al. (2001, 2004, 2012), corresponds to the narrative of the particular aspects of the teacher's practice, meaning how each teacher understands and thinks about teaching specific content in a certain way and time. Following the methodology of Loughran et al. (2012), each PaP-eR was composed of different parts representing each teacher's reflections related to the different PCK components proposed by Magnusson et al. (1999). By reviewing all the teachers' lessons, different situations were chosen in which the components of the initial CoRe generated by each teacher appeared. We included in the stimulated recall interview only extracts that were recognised by both authors as part of the same component of Magnusson et al.'s (1999) PCK model. Those extracts were discussed by both researchers in order to choose the most suitable situation accordingly to the initial CoRe.

The following presents an example of the questions asked and an excerpt from the lesson (as videoed) that was presented to the teacher Peter to contrast his opinion on the students' misconceptions of the subject of human evolution:

> Interviewer: In the initial interview, you suggested that the misconception you think that the children will declare is one of linearity and that humans are the most evolved. In the group interview, you suggest that some new misconceptions arise, like that we come from chimpanzees and that evolution has a final aim. Let's look at the following sequence, which was done after having constructed the timeline of different hominids (excerpt from 6:50–9:40):

T:	Now comes the fun part, first, this thing is linear or not linear. So, it's clearly a timeline, but there are species that coexist, meaning that they lived at the same time. Perhaps not in the same place, but there are species that coexist. We could say that H. habilis coexisted with P. boisei, that H. erectus perhaps coexisted with all of these. But these are the dates that we have from the fossils that have been found, look at this, with this and with this, now what happens to them now with the timeline? Remember one of the test questions that the line appeared like this, and what happens now when you see this and you compare it with the timeline that we just made?
Students:	It is not.
T:	How would it be then? How do you think that this would be?
St:	We do not come from chimpanzees.
T:	According to these data, we do not come from chimpanzees. What's up, Dylan?
St:	This just blew my mind.
T:	Excellent! I ask you Dylan, because this topic is important to me, because before you had a very logical idea, more or less. But the data that you found now, do they work for you or not?
St:	Yes.
T:	This means that you now changed your perception, but you changed it because these data worked for you. This is a topic because I can show you a lot of data, but you can continue, then, thinking the question is, all the evidence that we show, the skulls, the position of the foramen magnum, if there was torus or

sagittal crest, how they walked, does it tell you a bit more or break down the structure a bit that you had that said we came from monkeys?

St: Yes.

Interviewer: Do your ideas change about the misconceptions that the students have?

This structure is one that was achieved by considering all of the consulted components of PCK, specifically the central ideas, misconceptions, strategies and limitations, and methods of evaluating teaching, for each teacher about his/her knowledge on evolution after having completed the lessons.

Results

How do two biology teachers develop elements of PCK for evolution through their participation in a professional development programme that includes a follow-up in their classroom?

In Figure 1, the elements and relationships of Annie's PCK on evolution are represented. For her, the two central ideas before conducting lessons were speciation and diversity because, according to her, they are key concepts to understanding the origin of human being:

> Yes, the concepts of speciation and diversity and that they understand that we are talking about human evolution (…) To understand what we are, we have to understand everything back in time to make a comparison of what a person builds over time, which has been his/her family. Starting with that idea as well, that is, we are what we have explicitly inherited from our ancestors in our DNA and our whole history. (Interview 1)

Regarding students' misconceptions, she recognises that the idea of linearity in the evolution of man is the most important and intends to dismantle it by using different central ideas. In terms of difficulties in working with these topics, she describes that some are related to her training, such as the insecurity that she had about her knowledge of evolution; on the other hand, she acknowledges other external reasons, such as the Catholic orientation of the school. She admits that her strategies for teaching evolution in previous years were very traditional, with the reading of a text and then a presentation of certain concepts on evolution. In contrast, she now attempts to make a connection with some aspects of the NOS (such as the difference between theory and law) to explain various aspects of evolution. Regarding assessment, Annie believes that it is flexible because she understands that it should be built with the students, considering their responses.

After completing the lessons, Annie incorporates two new central ideas: components of natural selection and the idea that evolution is a gradual change. She acknowledges that there are some misconceptions that she did not consider, such as that evolution entails a rapid change or that it is at an individual level, based on the idea of survival of the fittest. On the other hand, she feels that the idea that humans are perfect beings is not significant as a misconception for the students. According to her, the strategies that she incorporated were to link evolution with aspects of genetics to explain that the change in evolution is gradual and to achieve some aspects of the NOS including the creativity of researchers and scientific inquiry. Assessment is an ongoing challenge, and she believes

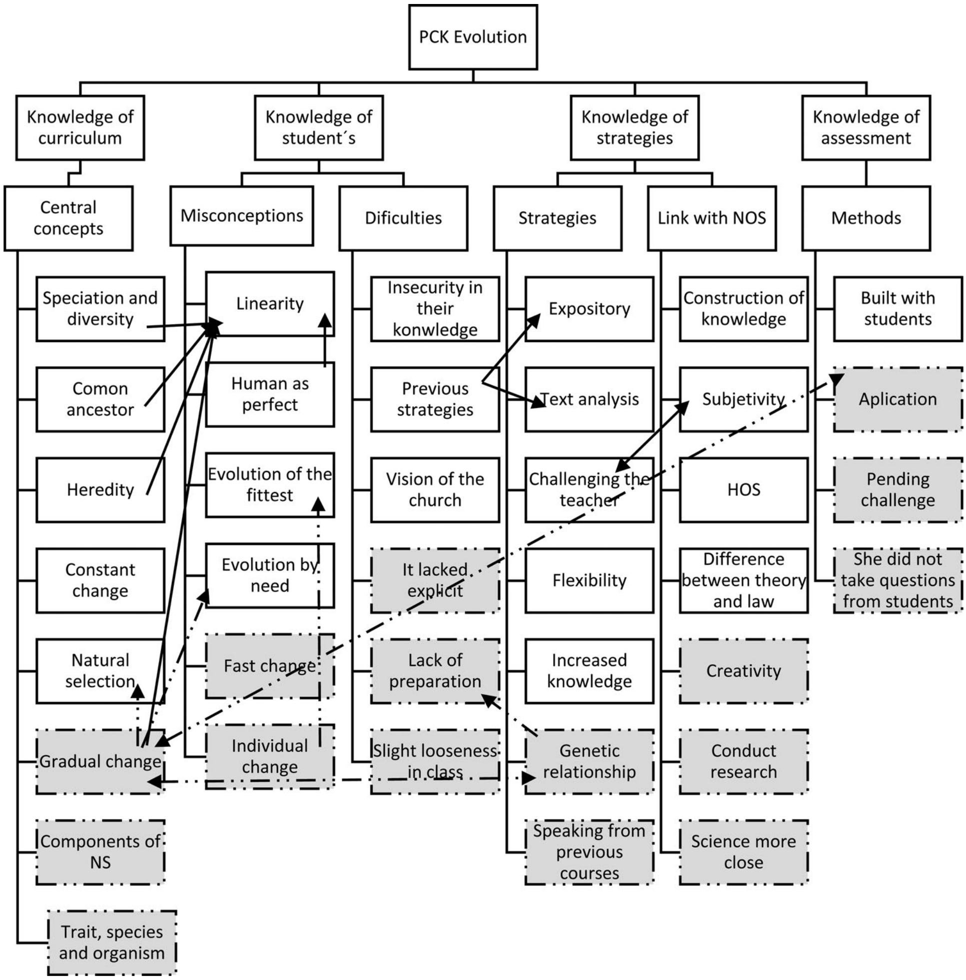

Figure 1. Scheme summarising the PCK components and network of teacher Annie on evolution.

that she did not take advantage of the students' questions and thinks that she missed more opportunities to apply them.

In Figure 2, the elements and relationships of the teacher Peter's PCK on evolution are represented. Before completing the lessons, he recognised the central idea that students understand what evolution is as a general concept:

> The main thing that they should learn is the concept of adaptation; they should also learn something about phylogeny, how organisms are related, analogous and homologous and vestigial organs. Just today, we were discussing a bit of that, what other things do they have to know? Variations and to have a perspective; from the start, they have to learn what evolution is, independent of the mechanism used having to explain evolution. But generally, I teach evolution as a change in the allele frequency in a population—that is evolution. (Interview 1)

As the most relevant misconception, Peter recognises the idea of linearity. For difficulties, he recognises his own knowledge on evolution, the school's Catholic view, the means of

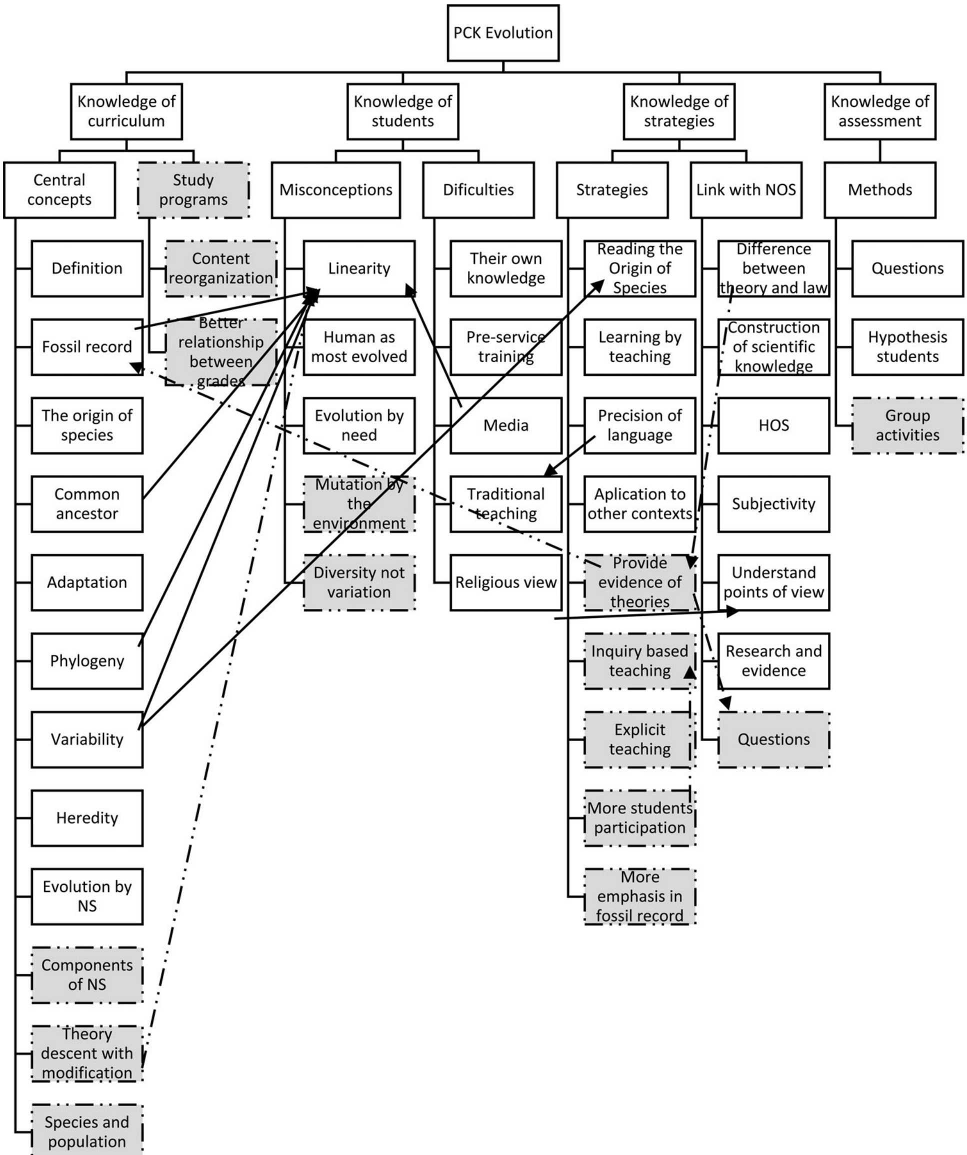

Figure 2. Scheme summarising the PCK components and network of teacher Peter on evolution.

communication, and traditional teaching. One strategy for him is the precision that language should have because traditional teaching could generate misconceptions:

> The issue of necessity is the most important; when I speak to the children about the structure and function of a cell, (…) I am going to allow you to tell me that the Golgi apparatus is for this purpose. But in evolutionary terms, the Golgi apparatus came about and fulfilled a determined function but not intentionally. But what is most likely is that people who study cellular biology always think in terms of its purpose. (Interview 1)

Finally, Peter establishes a relationship with the NOS and recognises that it is important that, before teaching evolution, he should work with aspects such as the difference between theory and law and the importance of using research to debate the TE as a valid scientific theory.

After implementing the lessons, Peter incorporates new central ideas, such as teaching the components of natural selection, the difference between species and population, and linking the theory of descent with modification to challenge the idea of linearity. He recognises that the concept of variability should relate to other topics such as meiosis, mutation, and species; therefore, he argues for the inclusion of these topics in the national curriculum and proposes that the curriculum is reorganised. He also recognises new misconceptions, such as mutation not being random but an effect of the environment, and students understanding variation as biodiversity, meaning that they think that variation involves different species and do not understand that there could be differences within the same species. As strategies, he proposes conducting more research to resolve the issue that students do not know how to create research questions. He also suggests providing more evidence on the TE, such as the fossil record (see Figure 2). In this manner, the weight of the TE could be understood, and the differences between theory and law discussed. Evaluation is also considered to be an ongoing challenge.

What elements of the biology teachers' PCK for evolution changed due to the PDP?

In this section, the PaP-eR associated with the PCK components described in the model by Magnusson et al. (1999) is presented. Each PaP-eR has different parts that describe key issues reported by the teachers. A summary of the PaP-eR and the parts associated with each component is presented in Table 4. The description below is just for those PaP-eRs that are more related to the teaching of TE, rather than those that are more related to pedagogical knowledge (PK) in general.

PCK component: knowledge of the science curriculum

Below, the PaP-eRs illustrate what the teachers changed after completing the class and reviewing their practice related to this PCK component. In this regard, two PaP-eRs stand out – one associated with the programmes, materials, and objectives established by the curriculum and the other associated with the central themes or ideas that these teachers differentiate in teaching the TE.

PaP-eR 2: what are the central concepts of evolution that students should learn?. This PaP-eR, which consists of five parts, illustrates the central ideas incorporated by teachers after completing the lessons and that are key to teaching evolution.

Part 2: Understanding the concept of variability and randomness

For Peter, understanding the concept of variability is a central theme so that the idea does not remain that there are only changes or mutations due to pressure from the environment but rather that it is a random process. Here, it also matters that the difference between species, population, and individual remains clear so that students think of diversity not

Table 4. List of PaP-eRs and its parts. In bold it is highlight the parts discussed in the text.

Component of PCK (Magnusson et al., 1999)	PaP-eRs	Subdivision	
Knowledge of science curriculum	PaP-eR 1: I think we should teach this content before!	Part 1: Teaching this content from early grades	Annie
		Part 2: Otherwise sequence	Peter
	PaP-eR 2: What are the central concepts of evolution that students should learn?	Part 1: Understand that evolution is a gradual change	Annie
		Part 2: Understand the concept of variability and randomness	Peter
		Part 3: Another central concept is the Theory of descent with modification	Peter
		Part 4: Understand difference between theory and law	Both teachers
		Part 5: What is a scientific fact?	Peter
Knowledge of studentś understanding of science	PaP-eR 3: What do our students know about evolution?	**Part 1: Evolution is due to purposeful need**	Both teachers
		Part 2: Humans comes from chimpanzees	
		Part 3: All is subjective	
	PaP-eR 4: What difficulties do our students have?	**Part 1: Differences between trait, species and organism**	Annie
		Part 2: We should give more time for the students to express their opinions	Both teachers
Knowledge of assessment in science	PaP-eR 5: I do not know if the students understood everything	Part 1: Assessment as a pending challenge	Both teachers
Knowledge of instructional strategies	PaP-eR 6: Strategies for teaching science	Part 1: Previous and new strategies	Both teachers
		Part 2: To explicit the content as a key	Both teachers
		Part 3: Language does matter	Annie
	PaP-eR 7: Strategies for teaching evolution	**Part 1: Relationship between evolution and NOS**	Both teachers
		Part 2: Fossil record use	Peter

only between species but also within a species. However, he realises that students confuse variability with species diversity:

> It's that, in general, this is a debate we've had too often already, and if I want to understand natural selection, evolution or change, I have to understand first that, within populations, individuals are not all equal because, if everyone were equal, faced with any pressure that affected their fitness, everyone would die or everyone would survive (…) I consider that concept to be important, and if there is no variability, nothing will happen. (Interview 3)

The teacher believes that there are certain topics that students should know before they learn about variability to make that concept clearer and to facilitate their understanding so that they later understand how it connects to natural selection, connecting it with what is presented in the curriculum content:

> I think that it is easy, but it is necessary to know how to do it, and I later realised that it was easy and at first not because you take some things for granted at the outset. Last year, you taught it, and they learned meiosis well, and there are various books where the causes and steps of meiosis appear everywhere (…) mutation is not discussed much in the second year of secondary school, and in the fourth year of secondary school, mutation is discussed. And it is vital to have those two things that we have but also to be very clear what type of mutations there can be and to first make a theoretical account in order to then talk about the concepts of species and mutation and having all that very clear (…) and one understands variability immediately, and afterward, one speaks about change in the environment and selection pressure. (Interview 3)

Part 4: Understanding the difference between theory and law

Regarding the link between the NOS and evolution, Annie recognises the importance of teaching NOS, not only because it is necessary to spend time on the contents separately, in this case on evolution, but also because students should know what laws and theories are to better understand the TE and not diminish its value:

> Every year. So when I spoke to them (…) I do not know what law I talked to them about if I told them about the law of gases; when they were younger, I only spoke to them about the content. Then, I told them, 'Yeah, this is the law of gases' and if I said law and if I said gases and if I said the thing about gases, it was the same. Until now, it was the same because it made no difference to them. (Interview 3)

Additionally, Peter recognises that understanding the difference between theories and laws is key to understanding the TE. He knows that the literature on teaching evolution highlights this aspect, and he now comprehends that relationship more clearly:

> Not so much conducting the lessons, by what I have read as well, and with my recent experiences, such as realising that, in reality, it is an issue and the literature says so, that one of the greatest problems regarding theories and laws is that theories appear as if they are not given importance. Furthermore, it is believed that they can never be proven, and now I give more importance to that as well, basically saying that there are some laws that support this, and I collect those laws and form or build something that is more powerful than a theory that explains many more things. Thus, speaking about human evolution and explaining why there is currently obesity and speaking about lactose intolerance, speaking about all of those things, you realise that, with the theory of evolution, many things can be explained, but with a law … you can't explain anything. (Interview 3)

PCK component: knowledge of students' understanding of science

The PaP-eRs that are presented below illustrate what the teachers changed after completing the lessons and reviewing their practice related to this PCK component. In this regard, two PaP-eRs stand out – one associated with students' primary misconceptions (*PaP-eR 3*) and the other associated with the topics about which students have greater difficulty when learning the TE (*PaP-eR 4*).

PaP-eR 3: what do our students know about evolution?. This PaP-eR, consisting of three parts (Table 4), illustrates students' main misconceptions that the teachers recognise after conducting the lessons; teachers think that some of the misconceptions were challenged successfully, while other misconceptions were more complex and difficult to change.

Part 1: Evolution is due to purposeful need

Annie knows that this misconception has its source in the everyday language used by students and by society in general, where the 'for what purpose?' of things is always spoken of in terms of intentionality:

> Yes, I believe that, in fact, the word need is inevitable than the survival of the fittest because one has needs, one is always being exposed to that or always says that things are for something, ah! And that is something else, (…) when one asks for explanations in the different lessons, not only on evolution, one always tries to ask the 'why' of things, and they always respond to you with the 'for what purpose' I do not know why; perhaps it is because it is easier to answer with the effects of things. (Interview 3)

Her proposal for working with this misconception is to link it with the central idea that change in evolution is gradual, to incorporate the idea of the process, in addition to understanding that it is at the level of populations. She considers it important to speak of these topics in earlier grades to model the language that is used.

Regarding this same misconception, Peter considers that he could indeed discredit the idea that evolution is due to needs, perhaps not in all students but in many. The strategy that worked most for him is related to the clarity and precision of the language he employed; many students took away from his explanations that change was necessary, meaning that organisms evolve because they need that change:

> Yes, your speech suggests the following, and in fact, to the third year students, I explained natural selection to them. I showed them a pair of videos and told them to bring materials next week because you all are going to make a model of natural selection. And I told them before presenting that the word that they could not say is need …
>
> I: For something.
> Peter: Yes, they could not use that, and if they used it, they are going to get a bad grade.
> I: So, given your current experience, that's how you restricted it.
> Peter: It's just that, I used it in a certain way to tell them that, within natural selection, there was not that concept of necessity, within that theory (…) and so if you are going to explain natural selection to me, I need you to name such or such or such thing; I need you to not mention need. And when I ask them, 'Why did this change?' they tried to explain it to me, and suddenly one student said out of necessity, and everyone said, 'Booo', and he realised it afterward. (Interview 3)

Part 2: Humans come from chimpanzees

Another misconception that the teachers thought would be present in students is the idea of descent from chimpanzees to humans. Annie recognises that her group of students brought this misconception with them and addressed it by working with an activity on constructing a phylogenetic tree:

> Yes! They were super convinced for some time that we did not come from monkeys, I did not know when we began to speak about that, but they knew it; even then, they produce the traditional timeline (…) now, at first, they agree, now that image is debatable because in no part of the image does it seem that one disappears and the other appears but rather that it can indicate to you who was first and who was after. But I believe that the key was that they had access to years in which they were all present and asking them if there had been coexistence of one with another. And that was when they realised that it is not like a little line but rather that there is a parallel, that chimpanzees exist now. I believe that, now I am sure that this is clear to them, with the idea that chimpanzees exist now and have existed the whole time and have cohabitated the whole time with humans, with *Homo sapiens* and also with others before; I believe that convinced them that such descent does not occur. (Interview 3)

Regarding this same misconception, Peter recognises that the solution is to work with the issues of phylogeny, variability, and common ancestry, although he acknowledges that he does not know if everything was clear because some students still kept the idea of the classic image of the linear change from chimpanzee to human:

> I do not know, I believe that it was clear to them that there are many hominids and that still it is unknown to which we are most related. I believe that, at some point, I showed them a little tree as more linear and without so many things from here or from there, and that was clear to them (…) but I do not know if it was clear that, in reality, we come from groups that are different from these.
>
> (…) That there are common ancestors, thus the later topic about chimpanzees and chromosomes, it gives you a better idea of that (…) and in fact, we needed an activity to show that and perhaps to see if DNA was found from someone and from some of these, to compare a particular gene. (Interview 3)

PaP-eR 4: what difficulties do our students have?. This PaP-eR, which consists of two parts (Table 4), illustrates the main difficulties that teachers saw in their students after having conducted the lessons. It is related to the previous PaP-eR in that they could be misconceptions that were not broken down.

Part 1: Difference between adaptive traits, species, and organism

Teachers also recognise concepts that are more complex to understand than others. In the case of Annie, when she relates the concept of species to the individual, she realises that this issue could be very important to clarify because it is complicated for students to distinguish between them, especially if they speak about adaptive traits as well:

> Of course in their case, that also would have to be confirmed, there are so many tasks for me to confirm because they know, when they speak in terms of organisation, they know how to define organism, they know how to define species, but here we are really applying those

> terms, and it is differently speaking about the fittest organisms and about the fittest species. (Interview 3)

She acknowledges that previously she had described the species concept poorly, or did not realise how this could influence others' misconceptions, but now, after the first part of the PDP, and having worked with her colleague on the lessons plans, she understands it better:

> No, the whole time I talked about (…) it is that perhaps we had not reflected on it much, but I always talked about the strongest individual, the fittest, the one who is most prepared, but always talking about the individual, and that leads to a lot of mistakes. (Interview 3)

PCK component: knowledge of assessment in science

This PaP-eR illustrates what the teachers know about what and how to evaluate students' primary learning related to evolution.

PaP-eR 5: i do not know if the students understood everything. The PaP-eR, which consists of one part, is related to the teachers' methods for evaluating the students' learning.

Part 1: Assessment as a pending challenge

For both teachers, the main situation related to this PCK component was the evaluation method; they know well what to assess in the teaching of evolution, but the methods for evaluating what the students learned remained unclear or challenging. Annie feels that, in terms of evaluation, she lacked a method to confirm whether students understood some important topics, such as whether they made the distinction between species, individuals, and adaptive traits. Furthermore, she thinks that she gave little opportunity for students to talk and give their arguments, given that she did not ask them or that the students were accustomed to not contributing to the class discussion. For Peter, the situation was similar; he considers the forms of evaluation to be things that did not happen and should be addressed later on:

> I: Are those your main lessons?
>
> Peter: Yes, it's like the word 'explicit', like something that has come up a lot. And another topic to improve, in addition to being explicit, is that of evaluation: how to evaluate this? That is the greatest challenge because, already, I can be very explicit, but I need to evaluate in order to have everything well-recorded and demonstrated well because questions were left open, and perhaps many of those questions were not asked with the next class in mind or were asked suddenly; there has to be a connecting thread. (Interview 3)

Despite this issue, Peter conducted a test upon ending the sequence where he requested the application of the components of natural selection and recognised that there were some students who continued to claim that evolution is a necessary change, but there were many students who made their explanations by considering variability and natural selection:

> However, in one of the tests that I did recently, (…) I gave students two texts with the following instruction: 'according to the following statements respond to the questions'. The statement said: leopards generated more musculature to run faster since their prey began to run faster, and then the first question was: do you consider this statement to be correct? And

> everyone reviewed natural selection and some told me, 'Yes, it is correct, and they had to develop it more by nature because, if not, they were going to die', and others told me, 'No, because it is suggesting that the generation of musculature is due to necessity and not talking about variability', and some gave that response on the test (Interview 3)

PCK component: knowledge of instructional strategies

The PaP-eR below illustrates that teachers changed their methods of teaching evolution after completing the lessons.

PaP-eR 7: Strategies for teaching evolution. This last PaP-eR (Table 4) includes specific strategies that teachers employ to teach evolution and NOS.

Part 1: Relationship between Evolution and NOS

Annie acknowledges that establishing a relationship with the NOS promoted an understanding of evolution. She believes that the initial lesson that they conducted on the NOS without evolution allowed them to work with aspects such as theories and laws, models, and subjectivity in science, among others. Furthermore, she thinks that she could utilise these aspects of the NOS for other topics and contexts as well:

> Yes, I liked it, and I continue to do it. And now I will proceed with evolution, I am beginning now, and I am going to do the same with the eighth graders because I believe that it is the way it works better. And, in fact, these same topics (…) Look, I was doing a completely unrelated substitute assignment at Pedro de Valdivia. We were talking about the nervous system, and I brought up the topic of volume a number of times, I began to talk about evolution, and the kids responded well: I used the tools in other contexts, and that helped me. (Interview 3)

Regarding Peter, he recognises the importance of this link, and, in evaluating his lessons, he believes that he should make a more explicit link with the NOS. For example, he could have spoken more about theories and hypotheses and about how phylogenetic trees are a form of hypothesis:

> One of the mistakes that we committed, and I think that I said it in the group interview, is that we never made the relationship between everything we saw in the NOS and everything we were going to see in terms of evolution. So, it ended up that, sometimes, we remembered it, and we worked with inference, observation, hypotheses, theories, and laws, and this is where it is seen, and we applied it. However, it was lacking. (Interview 3)

He recognises that the lack of this link was generalised in what they touched upon in the NOS and evolution. Considering this issue, he says that he should also teach that what come from books are studies and that knowledge is built with questions and evidence.

Part 2: Fossil record use

Peter believes that another strategy is to work with scientific evidence in the science. In light of that, the topic of fossil records, in addition to providing evidence for evolution, also serves to discuss the value of theory and evidence, which is closer to discussing the aspect of evidence of the NOS:

> Yes, because now I realise what could have been or what question I could have suggested, and they could have suggested a hypothesis according to the theory of descent with modification: Do we walk the same? For example, did we walk in a group? This type of question, and now one could use it more. I could then demonstrate it with evidence and could speak again about theories and laws that I could check and test a theory with this material. (Interview 3)

According to the teachers, what elements of this PDP were responsible for the modifications to their PCK for evolution?

In the group interview, the teachers reported the impact of the PDP on two important aspects: the first was on their perception of what the students learned, and the second on their own learning. Both teachers became more aware of the difficulties that students have, some of them generated by themselves, such as some perceptions generated by their use of language. They also recognised that their students improved their understanding of some topics or produced a better foundation, such as speaking about natural selection, specifically variability. The teachers also noted greater confidence in their students in raising their concerns or responses, and they used that greater opportunity to deliver their proposals and become more active in their learning.

Regarding what teachers learned at the end of the PDP and its follow-up, they noted that the opportunity to work together allowed them to receive feedback on their lesson plans and try out the lessons before conducting them, in addition to putting themselves in the place of the students to think of possible questions that they would ask:

> Peter: We chose the same ideas, like, we arrived at the same ideas, and if any of the two were wrong, we could discuss it. And in addition to preparing, we made the lesson plans; it was not as if we already were going to make this lesson plan, here it is, and we are responding
>
> Annie: And the same thing we asked of the children we asked of ourselves because, for us, it was most important that they debate and that they try to offer their opinion. (Interview 2)

On the other hand, planning jointly allowed them to clarify topics that they could address and topics that they could not, meaning that discussing how the lessons turned with their students, helped them change activities and topics to be more intelligible:

> Annie: We arrived at the same idea. Peter always had a more advanced class than I had, and we conducted them exactly the same way. I do not know if we were influenced by this, it could be, but there were always the same reactions, the same responses almost, they were more or less similar in each of the lessons. So, that also helped us because we could respond to questions like, What came up last time? What would you change? Why was this unclear? Then, it is necessary to go back to look at it: How do we see it? What material do we use? How do we see it? (Interview 2)

What the teacher's report as the most valuable aspect of working together and the PDP was the value of collaborative reflection as central for their own processes of learning:

> Peter: And I compare myself with the year before, and it is incredible, I believe that I learned a great deal, and I could relate things because I already understood the topic of NOS, and I spoke a bit about science in my lessons. But with this, it was with much more emphasis, and as it gave more of that and I learned more about

> human evolution, I learned things that I had no idea about that were still missing. So, it was great, very, very good. And when I plan, it's just that, I already have a couple of activities that who knows where they come from. But I'm only seeing them based on my own knowledge, only what I know, whereas if I can discuss with someone who knows as much as I do, I can arrive at other things, and I can ask other questions that could be more valuable, not necessarily that my questions are the most valuable. So sharing, for example, I remember the question that we had about ultraviolet radiation for applying natural section: that was a question that was very good to see if the children understood natural selection, those questions would not have occurred to me if Annie and I had not been planning together. (Interview 2)

For Annie, planning with Peter was also valuable because it allowed her to strengthen her knowledge and feel confident, which meant greater confidence when conducting lessons:

> Annie: Everything you said happened to us, I believe that I speak for both of us here: for us, it was very important to connect in every way and then to think because what ended up staying with me was what you said at first. We also did these training in the summer, we met various times here during the year, but even then, I felt super insecure about leading a class and talking. I feel that the students deserve someone who stands up in front of them … without being totally sure of what they are doing … And so I felt that, with the feedback from Peter, the class I would lead would be of much, much greater quality. (Interview 2)

Finally, the review of lessons after they were conducted and the discussion on the foundation of their actions was also highly emphasised, which is something that is not very common in teachers' practice. This emphasis meant changing their work based on what they were observing that worked and what did not:

> Peter: It is that I am reflecting on my practice, I am observing myself, I am seeing what things I can do much better and what things definitively I should not do and what things I can improve or incorporate. And that is the benefit of this, it's fantastic, and in fact, things occurred to me right away that I have to do. And it is not that I am a bad teacher because I did not do this, because a lot of these things are unknown, but rather because I consider that it is important because many of the children later go on to do science. (Interview 2)

Discussion

According to the current literature, the contribution of the present study is twofold. On the one hand, this is one of the first studies that tries to develop teachers' PCK on evolution by a PDP in the university with a follow-up study in the school (Glade & Goldstons, 2015; Sickel & Friedrichsen, 2013). There are few examples of studies on PDPs that focus on improving the knowledge and acceptance of evolution by in-service teachers (e.g. Crawford et al., 2005; Ha et al., 2015) and even fewer that address the study of teachers' abilities to teach these contents and evaluate how teachers manage students' misconceptions (van Dijk, 2009). With regard to the issue of teaching evolution, some studies suggest that an understanding and acceptance of the TE may be influenced by an understanding of the NOS (Gregory, 2009; Ha et al., 2015; Lombrozo et al., 2008). The two teachers in this study also recognise the importance of this connection, especially in the first lesson that they conducted in which they teach the NOS without any associated content in an explicitly and reflective way. However, they believe that they largely missed clarifying the link that they hoped to make between the TE and the NOS. The teachers state that they should explicitly teach aspects of the NOS starting in early grades (primary school) because an understanding of the NOS facilitates acceptance of the TE (Großschedl, Konnemann, & Basel, 2014). One of the explicit linkages that the teachers made for the acceptance and understanding of the TE is going deeper into the importance of discussing scientific facts or evidence that support evolution and natural selection. Although one of the teachers recognises that he worked with this aspect in his class, he states that he missed providing more opportunities to discuss the studies and evidence that strengthen the theory. This finding is consistent with what Lombrozo et al. (2008) note with regard to the importance of understanding some aspects of the NOS that are key to accepting the TE, such as the nature of scientific theories.

The main misconception that teachers identified as linked to natural selection is that change is produced by purposeful need (Kampourakis, 2014). Given that misconception, during the implementation of their sequence, Annie and Peter decided to conduct an extra lesson that was especially dedicated to discuss components of natural selection to tear down that misconception. On the other hand, religious belief, specifically the idea of creationism, or anti-evolutionary ideas, although named by teachers at the beginning of the study, are not raised as significant obstacles to the intervention's aim at the end. This is consistent with what is described in the literature, in which some authors such as Kampourakis (2014) affirm that, more than creationism, there are cognitive and emotional obstacles that greatly influence the understanding of the TE by students. Großschedl et al. (2014) have proposed a similar conclusion. In their research with pre-service biology teachers, they find that religion should not be considered an obstacle to the acceptance of the TE.

The second contribution of this study is related to the methodology proposed for capturing the development of PCK through CoRe and PaP-eRs (Loughran et al., 2004) associated with components of the PCK described in the model by Magnusson et al. (1999). As illustrated above, the PCK of teachers is dynamic, different in each situation, and particular to each teacher (Berry, Loughran, & van Driel, 2008; Shulman, 1986). With Annie and Peter, differences are observed in the strategies for addressing the same content, given that they consider the context, their group of students, and what they know about how their students learn. From there, they conduct different lessons, although they have planned together. Therefore, this study confirms that teachers have a unique way of looking at their practice (Berry et al., 2008; Shulman, 1987). The transformation of practice is produced by modifying all the components of PCK (Magnusson et al., 1999). In other words, if only one component of PCK is changed, a transformation of practice will likely not be obtained. With Annie and Peter, it was possible to observe the emergence of new elements in the components of PCK, in addition to how each component relates to the others, which means that everything relates in different and complex ways (Magnusson et al., 1999). In this particular case, the relationships that are established, in addition to the change or emergence of a new element in a component, affect and influence another component, triggering the growth in the complexity of both teachers' PCK schemes of evolution. All the above is reflected in what Shulman (1987) calls 'the new comprehension'; in this case, it is these teachers' new understanding of how to teach evolution which is particular to each teacher.

One way to explain the differences between PCK and its modifications by both teachers is related to each PCK being varied because each classroom experience is unique and the experiences of these teachers enrich the development of PCK: although it is the same specific content addressed, the development of PCK will be distinct (Loughran et al., 2004). Their years of experience could also have an influence, resulting in different ways of understanding teaching (Kington, Reed, & Sammons, 2014). Furthermore, as Magnusson et al. (1999) suggest, the above can be related to their initial professional knowledge and its influence on PCK. For example, one of the teachers has greater subject matter knowledge (SMK) on evolution (Peter) (see also Table 2) and the other has more years of experience (Annie) which could be related to greater PK, which will mean a distinct influence on PCK and its development in both cases and, therefore, different emphases on the methods of teaching this content to their students.

Regarding the type of PDP experienced, these more complex relationships are produced, according to the teachers, due to their review of and reflection on the lessons they taught. This type of approach, in which PCK modifications are analysed based on what teachers observe upon reviewing their lessons, is related to what Loughran et al. (2001) claim about looking at PCK in action. In this sense, after the PDP and follow-up on the lessons taught, the teachers are aware of their PCK on evolution, recognising the strategies used, future challenges, and new activities that they will perform. Teachers who are aware of their knowledge can transform their practice (Nilsson, 2014) and learn from their own experience (Loughran, 2014a).

This research stands out because the teachers themselves report the changes in their understanding about how to teach the topic (as a result of reviewing their lessons). Furthermore, it achieves a novel connection between the model of PCK components of Magnusson et al. (1999) and a method for capturing PCK that Loughran and colleagues propose. This connection allowed the researchers to understand the framework (defined by the model) in which these teachers' development or modification of PCK on evolution operates. Given this proposal, it is possible to better identify the central ideas, the misconceptions and what they generate and the strategies that can be used to work with those ideas. The aforementioned is associated with what Loughran et al. (2001) describe the use of the CoRe and, in this specific case, it is refined by connecting it with the PCK components described in the model by Magnusson et al. (1999).

Finally, this study shows how the teachers redefine their teaching practices on evolution. Although they acknowledge various shortcomings in their lessons or aspects for improvement in how they worked with this topic, Annie and Peter know that they generated a different attitude in their students, who are now more active and curious. Furthermore, they realise that, when the students do not understand something well, they make pedagogical decisions to address that issue. These teachers are responsible for the students' learning, given that they feel that the students' success or failure depend on them (González-Weil et al., 2012), and they do not attribute success or failure to external obstacles, such as the students' lack of motivation or disinterest (Vázquez, Jiménez, & Mellado, 2010). Rather, they constantly seek to improve their lessons to enhance their students' learning.

Conclusion, limitations, and implications for science education

The proposal on how to capture PCK presented here provides a meta-cognitive look at teachers' learning because it is they who reflect on how and why their learning changes with regard to how to teach certain specific content. We want to emphasise that changes in the methods of teaching some content are clear for these teachers, who think that the information generated in the research is useful for them, beyond how useful it is, in this case, for researchers and the capture of PCK (Berry et al., 2008). During the PDP, teachers reviewed their teaching methods, their beliefs, their knowledge, and their self-efficacy, after which they redefined how they would teach evolution. Additionally, they increased their knowledge about the relationship between the content to be taught, the influence of their actions, the strategies that produce the best results, and the most important issues that they should address with their students in mind, including some of the aspects of PCK. Given the above, it would be possible to continue deepening this knowledge in teachers due to the PDP, the reflection on their practice, and their commitment to students' learning.

This research points to a PDP where a more collaborative method for enhancing the transformation of practice is favoured (González-Weil et al., 2014). In this case, teachers and researchers explore how students' knowledge of evolution could be made more understandable. Furthermore, this review of and reflection on practice increases knowledge of the content and about how to teach it in each teacher's own way, given their initial professional knowledge, their years of experience, and their context.

The relationship between teachers and researchers, in this collaborative example, also influenced the results found. The integration of knowledge from both sides undoubtedly generated a new way of understanding how to teach evolution for the two groups of students involved in the study and how to understand the opportunities for professional development for teachers.

In spite of the contributions of the study, we can also identify some limitations, which were mainly associated with the nature of the investigation. For example, the small number of cases do not permit the inference of more general conclusions about the relationships between teachers' PCK elements, or between teachers' PCK and the other components of teachers' knowledge (SMK and PK). In addition, because Annie and Peter teach only one class each, we cannot assess the effect of the teachers' lessons on the students' gain in knowledge about evolution and NOS. However, both issues could be new avenues of research, which could improve our knowledge about PCK development and about the best strategies for teaching evolution to students.

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