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A map of collective pedagogical content knowledge as a basis for studying the development of biology teachers' personal PCK of evolution

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ABSTRACT

In the past few decades, a large body of research has been conducted on pedagogical content knowledge (PCK), but further empirical and theoretical studies are needed to enhance our understanding of PCK development. This study aimed to describe the development of PCK of evolution in a group of biology teachers using a modified version of the refined consensus model (Mixed Model), including the five components of PCK from the model elaborated by Magnusson et al. (1999). The qualitative research design involved multiple study cases, including semi-structured interviews and lesson plan meetings. A collective PCK (cPCK) map was generated via content representation interviews with six expert biology teachers and scholars. The ideas expressed by three or more experts were then included in the cPCK map, which was used to assess the personal PCK (pPCK) development of a different group of seven biology schoolteachers using three traits: map area, map shape, and the identity of the concepts included in the map. The findings show that the development of teachers' pPCK was mainly due to the increase in the map area resulting from the inclusion of new concepts belonging to knowledge of students learning and to the knowledge associated with strategies.

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Pedagogical content knowledge; PCK Mixed Model; natural selection; collective PCK; personal PCK

Introduction

Pedagogical content knowledge (PCK) has been of great interest to researchers in science education for the last two decades (Van Driel et al., 2023). However, there is still debate about how teachers' PCK development can be characterised (Chan & Hume, 2019; Schiering et al., 2023; Van Driel et al., 2023), and models for understanding and representing PCK continue to be created or modified (e.g. Behling et al., 2022; Carlson & Daehler, 2019; Park & Chen, 2012).

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According to a literature review by Chan and Hume (2019), teachers' PCK can be develop over time because of different experiences, such as professional preparation programmes and teachers' classroom experiences. However, the mere experience of teaching is not enough to guarantee the development or sophistication of PCK (Friedrichsen et al., 2009; Park et al., 2020). In fact, there is contradictory evidence regarding the relationship between years of experience and PCK (GroBschedl et al., 2015). Subject matter knowledge (often also referred to as content knowledge, short CK) could also be required for the development of PCK (Rollnick, 2017; Schiering et al., 2023). In addition, PCK development may be affected by teachers' beliefs about teaching and learning science (Carlson & Daehler, 2019; Friedrichsen et al., 2009; Mavhunga & Rollnick, 2016; Schiering et al., 2023).

From a methodological perspective, the literature mentions diverse aspects that have been used to describe how teachers' PCK develops (e.g. Friedrichsen et al., 2009; Mavhunga, 2019; Van Driel et al., 2023), but rarely are these aspects directly connected to the properties of the models stated in the conceptual frameworks of prior studies (Park & Chen, 2012). In this context, the pictorial representation showing the interactions of PCK's components or the PCK map created by Park and Chen (2012) is the main attempt to make the connection between PCK development and the model's components more visible (but see Chan, 2022), including the five components of Magnusson et al.' (1999) model, the orientations to teaching science (OTS), the knowledge of science curricula (CuK), the knowledge of students' understanding of science (KS), the knowledge of assessment (KA), and the knowledge of instructional strategies (KIS). With this framework, Park and Chen (2012) highlighted that the quality of PCK depends on the coherence among these components as well as the strength of individual components, and that the connection between two components (e.g. KS and KIS) influences both proprieties (Park & Chen, 2012) (see Figure 1 for a summary of the main PCK models used in this study).

Similarly, Carlson and Daehler (2019), in their description of the new refined consensus model (RCM) of PCK, defined two different types of PCK – collective and personal – but did not mention any of the five components of PCK included in previous models (e.g. Magnusson et al., 1999; Park & Chen, 2012). They defined collective PCK (cPCK) as 'a specialized knowledge base for science teaching that has been articulated and is shared among a group of professionals, which is related to teaching that particular content to particular students in a particular learning context' (Carlson & Daehler, 2019, p. 86), and personal PCK as 'the cumulative and dynamic pedagogical content knowledge and skills of an individual teacher that reflects the teacher's own teaching and learning experiences, along with the contributions of others' (Carlson & Daehler, 2019, p. 85). If we assume that cPCK includes consensual knowledge built by a community of teachers, scholars, and researchers who have taken what the literature says and linked it to their experience in teaching a particular topic and context, we could propose using cPCK to make a comparison with a science teacher's personal PCK (pPCK) at different times; this could allow us to evaluate the changes in his/her pPCK over time.

Teaching and understanding evolution is one of the topics with the greatest development in science education in recent years (Cofré et al., 2023; Harms & Reiss, 2019; Wang et al., 2023), and many studies on the PCK of evolution (PCK_{evo} thereafter)

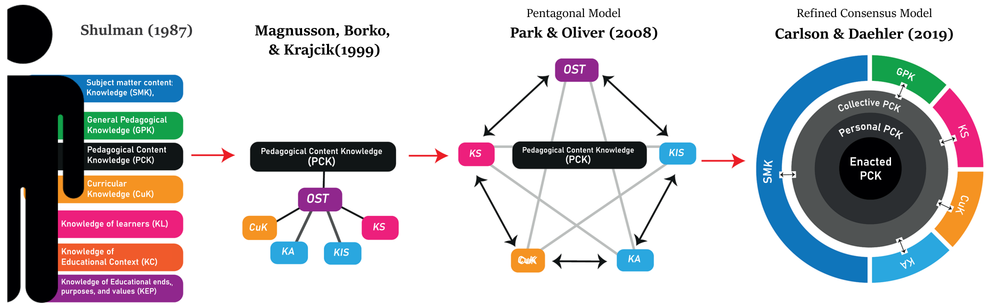

Figure 1. Diagram of the historical development of the main models of PCK from Shulman to the Refined Consensus Model (Carlson & Daehler, 2019). The colours indicate the different knowledge identified in each model. All colours are recognised in Shulman's first proposal, except the knowledges in light blue which are first incorporated in Magnusson et al.'s model (1999), KA = Knowledge of Assessment and KIS = Knowledge of Instructional Strategies. The other colours are green (general pedagogical knowledge , GPK), black (pedagogical content knowledge, PCK), orange (curricular knowledge, CuK), pink (knowledge of learners or students, KS), brown (knowledge of context), purple (knowledge of the purposes of education). This last knowledge recognised by Shulman is assumed to be analogous to the orientations to teaching science, OTS, of the Magnusson et al.' model (1999). Each model has been simplified to highlight the similarities and differences in teacher' knowledge. The PCK is shown in black to highlight its location and relationship to the rest of the teacher's knowledge. In Shulman, PCK is one of the seven knowledges. In Magnusson et al., PCK is made up of 5 components, the same as in the pentagonal model. Finally, in the RCM, the PCK is again a single knowledge in which no other component is distinguished. In addition, other knowledge recognised by Shulman but not incorporated in the 5-component models reappears.

have been conducted in the past decade (e.g. Bravo & Cofré, 2016; Fischer et al., 2021; Friedrichsen et al., 2018; Gao et al., 2021; Hartelt et al., 2022; Lucero et al., 2017; Sickel & Friedrichsen, 2018). For example, in a literature review about PCK_{evo} for teaching at the university level, Ziadie and Andrews (2018) found that out of 316 papers analysed, 75% focused on instructional strategies, 21% addressed student thinking, 8% dealt with assessment, and 2% concentrated on goals about teaching evolution. Hence, it is possible to think of the existence of a canonical or theoretical PCK for teaching evolution.

According to this context, this study aimed to describe the pPCK development of a group of biology teachers in the context of teaching evolution, using a cPCK as a reference. Here we present a new PCK model called Mixed Model, a modification of the RCM of PCK (Carlson & Daehler, 2019) including the components of Magnusson et al.'s model (1999).

Theoretical framework

Pedagogical content knowledge models

At first, Shulman (1987) proposed seven categories of knowledge that could be recognised in teachers (the first model in Figure 1). More than ten years later, Magnusson et al. (1999), based on the previous work of Grossman (1990) and Tamir (1988), proposed a PCK model composed of five components (the second model in Figure 1).

Although Shulman originally considered curricular knowledge to be a separate domain of knowledge, Magnusson et al. (1999) included it as part of PCK. Furthermore, although not explicitly stated, the PCK components of orientations and student knowledge could also be distinguished as independent PCK knowledge in Shulman's (1987) first proposal (see the colour similarity in Figure 1). Finally, this model clearly incorporates assessment knowledge into teachers' PCK since it was not included in the original list of knowledge provided by Shulman (1986, 1987). Thus, in the Magnusson et al.'s model (1999), PCK becomes a form of complex meta-knowledge comprising five other types of knowledge (components) that are related to each other. One of the most widely used modifications of this second model is the proposal by Park and Oliver (2008), who elaborated on the pictorial representation or PCK map of the interactions of the five PCK components from Magnusson et al.'s model (1999) (Park & Chen, 2012) (the third model in Figure 1). According to Park and Chen (2012), in the study of PCK components, it is possible to recognise the strength (i.e. the number of connections) between two components and the coherence, represented by the equality with which they are linked in the overall PCK map. The analysis of these interactions indicates that integrations between components are idiosyncratic and content-dependent, that knowledge about strategies and students' ideas generally possesses more connections, and that this evidence led Park and Chen (2012) to propose that 'the quality of PCK depends on the coherence among the components as well as the strength of individual components' (p. 922). Thus, the pentagonal model maintains the independence of PCK from other knowledge outside of it.

With the quest to integrate PCK into a professional development model, a consensus model (CM) was generated by Gess-Newsome (2015). Despite how attractive the model seemed in terms of coherence and the integration of PCK with other knowledge, context, teaching practice and students, this model was no longer popular as a new PCK model was generated. According to this new Refined Consensus Model (RCM) (the fourth model in Figure 1), the centre is content-based teaching practice (Carlson & Daehler, 2019). A key feature of this new model is the identification of three distinct types of PCK – cPCK, pPCK, and ePCK – which are described as specialised professional knowledge possessed by multiple teachers in a field (e.g. evolution) (cPCK), the personal professional knowledge possessed by an individual teacher (pPCK), and the unique subset of knowledge that a teacher uses when making pedagogical choices during planning, teaching, and reflecting on his or her lessons (ePCK), respectively (Park & Chen, 2012). In this representation, PCK is again modelled as unique knowledge, without other knowledge included as components, and some of the knowledge proposed by Shulman is again included as well as the knowledge of assessments added by Magnusson et al. (1999).

Development of science teachers PCK

There are multiple interpretations of what PCK development means and multiple ways to operationalise it; for example, increasing coherence/connection between PCK's components, enhancing the quality of each component, expanding instructional strategies, aligning with key ideas, and ensuring the quality of the relationship with other knowledge (Van Driel et al., 2023). Researchers have used a variety of methods to assess PCK development (Chan & Hume, 2019). For instance, Friedrichsen et al. (2009), in one of the most cited empirical studies on the development of PCK including four science teachers attending an alternative certification programme, concluded that, 'the continued development of teacher knowledge will require continued modifications to our representations of that knowledge' (p. 375). Although Friedrichsen et al. (2009) used Magnusson et al.'s PCK model (1999) to inform their data collection and analysis, the knowledge representation they presented for the teachers involved was an alteration of this model, in which pedagogical knowledge and SMK are also included, and the teaching orientation is outside of the PCK. In another example, Mavhunga (2019) investigated the PCK development of pre-service physics teachers using the RCM as a conceptual framework (which is employed in the methodology for defining PCK development); it includes indicators such as the learner's prior knowledge, curricular saliency, what is difficult to understand, representations, and conceptual teaching strategies. Similarly, Schiering et al. (2023) used the RCM as a conceptual framework to describe PCK development; they recognised SMK, teaching experience, and adequate beliefs about teaching and learning as important factors promoting PCK development without explicitly or pictorially relating these variables to the RCM diagram. Finally, PCK models have been found to visually express PCK factors or components (Bravo & Cofré, 2016; Park & Chen, 2012; Reynolds & Park, 2021; see also Chan, 2022).

Teaching, learning, and PCK for evolution

Many biology teachers around the world have problems both in understanding evolution and in accepting it as valid scientific knowledge (Cofré et al., 2017). Thus, they also have problems teaching this content. One of the constraints that makes it difficult for biology teachers to teach evolution correctly is their lack of training in relevant teaching strategies (Romine et al., 2014; Sickel & Friedrichsen, 2013). Teaching and understanding evolution is one of the topics with the greatest development in biology education (Cofré et al., 2023; Wang et al., 2023). For example, the study of students' thinking about natural selection has focused on three main cognitive biases (i.e. essentialism, teleology, and intentionalism) and how they impede the understanding of evolutionary concepts (Nehm, 2018). The study of students' comprehension has shown that students can use mixed explanations reminiscent of pre-Darwinian scientific explanations (Chi et al., 2012; Nehm & Ha, 2011). Nehm and Kampourakis (2016) proposed describing students' thinking based on its components (scientific and non-scientific elements), structure, and coherence. After analysing the composition of students' explanations, Nehm and Kampourakis (2016) established that a student can combine need-based reasoning with the scientific ideas of mutation and inheritance to build a mixed response (Cofré et al., 2018; Parraguez et al., 2023; Zabel & Gropengiesser, 2011). Evans et al. (2012) suggested that understanding natural selection requires a 'radical' conceptual shift in which students must switch from a naïve psychological explanation that uses an anthropomorphic argument to a naturalistic explanation that avoids purpose and endorses the idea that species can undergo significant change. This knowledge of students' understanding has informed the instructional strategies that should be used for teaching evolution (Harms & Reiss, 2019). For example, the inclusion of the nature of science (NOS) is useful not only for contributing to the discussion and differentiation between scientific knowledge and religious beliefs, but also for showing students that evolution is both a fact and a good scientific theory with solid evidence and great explanatory power (Cofré et al., 2018; Kampourakis, 2020; Parraguez et al., 2023; Scharmann, 2018). Finally, one of the most effective ways to assess learning about natural selection is for students to apply their knowledge to various evolutionary contexts (Cofré et al., 2018; Nehm, 2018), for which the instrument most widely employed in the literature is the Assessment of Contextual Reasoning about Natural Selection (ACORNS) (Nehm et al., 2012).

Due to all this information collected in the past 30 years about teaching and learning evolution, research on PCK_{evo} is also increasing (e.g. Becerra et al., 2023; Fischer et al., 2021; Friedrichsen et al., 2018; Gao et al., 2021; Hartelt et al., 2022; Lucero et al., 2017; Sickel & Friedrichsen, 2018). Lucero et al. (2017) investigated four teachers at a secondary school in the US and found that they were not using the preconceptions of their students to direct their teaching; these conceptions were only corrected or not acknowledged. Gao et al. (2021) used a PCK map to study an experienced biology teacher and found that knowledge of instructional strategies and knowledge of science curricula were the most connected with the rest of the knowledge, and that productive reflective episodes can help biology teachers to cultivate PCK. Many quantitative studies have focused on pre-service biology teachers' knowledge about students' preconceptions (Fischer et al., 2021; Hartelt et al., 2022). Hartelt et al. (2022) examined the development of PCK_{evo} in pre-service and in-service biology teachers and found that the ability to diagnose and address preconceptions correlated with teachers' SMK and acceptance of evolution. Furthermore, teachers with more experience (in-service) often suggested correct approaches to address student conceptions than pre-service teachers did.

The current research

In the past 10 years, our study group has had experience in implementing a professional development programme (PDP) for teaching evolution, in which more than 50 teachers have been involved and whom we have accompanied in the execution of their lessons (Cofré et al., 2017). Between 2013 and 2021, our experience was quite successful since most of the biology teachers who participated in the first part of the PDP (meetings at the university) developed skills to create lesson plans aligned with a sophisticated PCK_{evo}. In the case of a small group of teachers, our accompaniment has gone beyond university sessions to work in their schools (Becerra et al., 2023; Bravo & Cofré, 2016). Systematic, long-term work with a group of biology teachers – in which theoretical knowledge from research as well as practical experiences of innovation and follow-up in the classroom interact – allows us to recognise a community of teachers and scholars who share knowledge on evolution education or a $cPCK_{evo}$ according to Carlson and Daehler (2019). The specific questions that guided this research are as follows:

(1) What are the key concepts that make up the cPCKevo of a group of expert biology teachers and science educators who teach evolution in Chile? (Study I).
(2) What does the development of the pPCKevo of a group of biology teachers look like in relation to cPCKevo? (Study II).

Methodology

Definition of collective PCK$_{evo}$ in Chile (Study I)

In a collaborative work of reflection, our group of biology teachers and science educators proposed a modification to the RCM model of PCK (Figure 2). The model includes each of the components recognised by Magnusson et al. (1999), represented by each of the triangles that form a pentagon, and includes the three realms of the RCM (enacted, personal, and collective) as well as two other components: teaching context and personal knowledge and beliefs (Figure 2). Therefore, we called it a Mixed Model. A teaching context is included between personal and enacted PCK because science teachers usually point out that the context of the school (e.g. the number of students in the classroom, the absence of a laboratory) influences their practice and therefore acts as a filter or

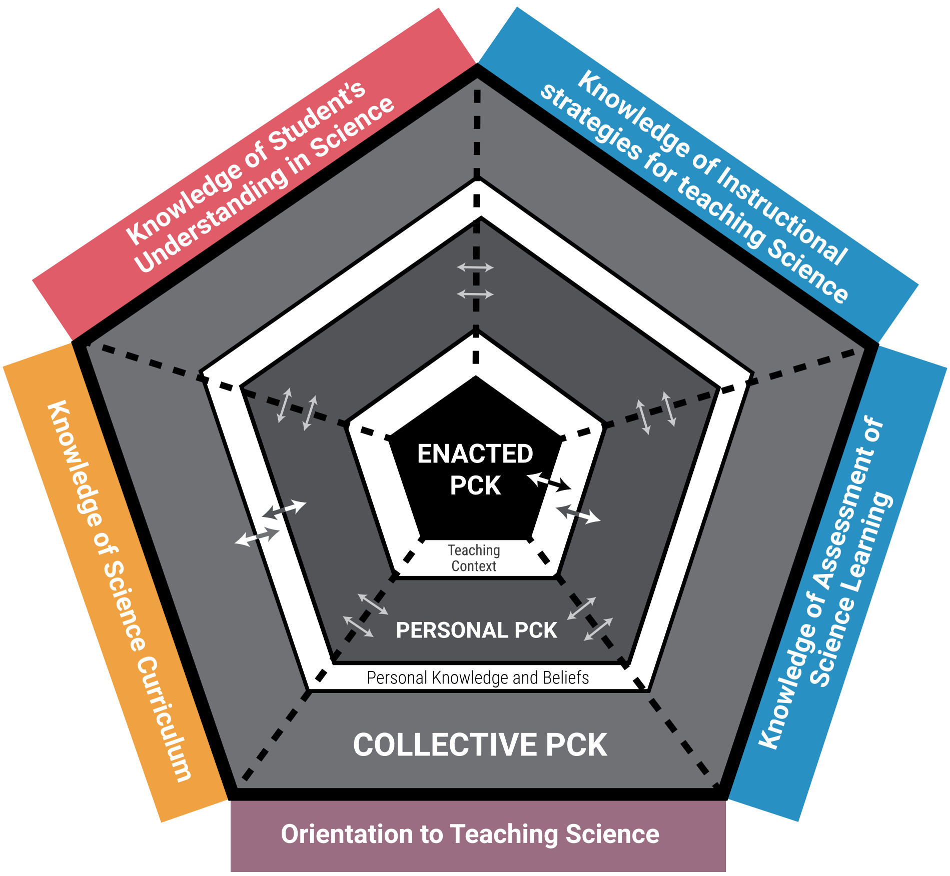

Figure 2. Representation of the new Mixed Model of PCK. This model includes elements from Refined Consensus Model (Carlson & Daehler, 2019) and from the five-component model (Magnusson et al., 1999). From Magnusson et al.,' model, its five components are represented by each of the triangles that form the pentagon. From the RCM, the model includes the three realms of PCK: collective, personal, and enacted. Between the collective and the personal PCK the model includes personal knowledge and beliefs of the teacher. Between personal and enacted PCK the model includes the teaching context for the practice.

amplifier between what the teacher knows and what he or she can implement. We also included a layer of other teachers' knowledge and beliefs (e.g. SMK or beliefs about science teaching and learning) between pPCK and cPCK because these aspects have also been proposed to influence PCK development (Carlson & Daehler, 2019; Friedrichsen et al., 2009; Mavhunga & Rollnick, 2016; Schiering et al., 2023). According to our Mixed Model and following the definition of Carlson and Daehler (2019), we recognise cPCK for evolution as knowledge held by science educators and experienced biology teachers in Chile for teaching evolution in ninth grade ($cPCK_{evo}$).

The Chilean context for teaching and learning evolution has many characteristics that have been described in the literature and international conferences, such as a curriculum with a learning progression that includes teaching evolution before genetics (Parraguez et al., 2023); a high acceptance of evolution as scientific knowledge by teachers and students (Becerra et al., 2023; Cofré et al., 2018); in-service biology teachers with low development of PCK_{evo} (Bravo & Cofré, 2016; Cofré et al., 2017); and many other contextual features (See also Becerra et al., 2023; Cofré et al., 2015).

In the second semester of 2020 (August – December), we started to build $cPCK_{evo}$ by holding content representation (CoRe) interviews (Loughran et al., 2012) with six science educators and biology teachers who have been working together to teach evolution over the past ten years. Table 1 provides information about the six experts who participated in the creation of $cPCK_{evo}$.

The six experts' CoRe interviews were audio-recorded and transcribed in full, and a qualitative data analysis was conducted, where conceptual coding (Miles et al., 2019; Saldaña, 2015) was guided by theory on PCK (e.g. Gao et al., 2021; Forsler et al., 2024). Through an inductive process, textual excerpts were selected from the interviews, and by interpreting the narrative of the excerpts, codes were created and classified (Miles et al., 2019; Saldaña, 2015). Subsequently, in a deductive process, the codes were grouped into broader categories corresponding to the PCK components of Magnusson et al. (1999) (e.g. Bravo & Cofré, 2016). To establish confidence in the coding process, two

Table 1. Academic and professional characteristics of six biology teachers and science educators who were included in the construction of collective PCK for evolution ($cPCK_{evo}$).

Participants	Academic and profesional Traits
Science Educator (Male)	Bachelor's in biology. PhD in Biology. Post doc in Science Education. Experience teaching evolution at university (2005 – present). Experience in research on evolution education (2011 – present).
Science Educator and biology teacher (Male)	Bachelor's in biology. Certified biology teacher. Master's in education. Experience teaching evolution at secondary school (1997–2005) Experience in research on evolution education (2011 – present).
Science Educator and biology teacher (Female)	Bachelor's in biology. Certified biology teacher. Master's in science education. Experience teaching evolution at secondary school (2008–2015). Experience in on evolution education (2014 – present).
Biology teacher (Female).	Bachelor's in biology. Certified biology teacher. Master's in science education. Experience teaching evolution at secondary school (1997 – present). Participation in research projects and PDP in PCK_{evo} (2015 – present).
Biology teacher (Male).	Bachelor's in biology. Certified biology teacher. Experience teaching evolution at secondary school (2011 – present). Participation in research project and PDP in PCK_{evo} (2014 – present).
Biology teacher (Female)	Bachelor's in biology. Certified biology teacher. Master's in science education. Experience teaching evolution at secondary school (2016 – present). Experience in research on evolution education (2016 – present).

researchers oversaw the coding data from each of the six experts and then met and discussed each score to reach an agreement. A range between 85% and 96% agreement was recorded between the reviews of both researchers for each expert participant, and the total number of disagreements was settled with a third researcher. After that, code networks were built using the ATLAS.ti programme (ATLAS.ti, 2021), and an 'image' of each scholar/biology teacher's PCK was constructed. The total number of codes recognised by the six experts after the consensus of the two researchers fluctuated between 22 and 33.

As a first form of consensus about $cPCK_{evo}$, only those codes whose frequency was greater than or equal to three were included in the preliminary proposal. The online supplementary material contains examples of quotes where a code was identified, explicitly named by an expert during the interview, as well as its frequency, name, and association with the Magnusson et al. (1999) categories. Thus, the first $cPCK_{evo}$ included 22 codes. As a second stage of validation of this $cPCK_{evo}$, the map was shared and discussed with 10 other biology teachers belonging to the same community in a workshop during April 2021. All 10 participants in this session also had experience teaching evolution at school and researching the teaching of evolution. In this workshop, two groups of five biology teachers analysed the relevance and pertinence of the 22 consensus codes and made suggestions for review. The proposals of each group were addressed in a plenary session (all 10 participants), at the end of which the final $cPCK_{evo}$ proposal was agreed upon (Figure 3). The suggestions for review were that the codes 'working with empirical data' and 'using current research' be merged into a single code as follows: 'using current research'. In addition, the alternative conceptions that 'human beings come from apes' and 'evolution is by use and misuse' were eliminated because there was a consensus that although they are described in the literature, they do not have great importance regarding frequency in the Chilean context. Finally, the code of 'evolutionary literacy' was incorporated into the orientation component by adding it to the objective of 'explaining phenomena of daily life'. Hence, after this second round of validation, the cPCK was composed of 20 codes distributed through the five components of the PCK model proposed by Magnusson et al. (1999) (Figure 3). One example of a code description is 'fossil evidence not in depth'; this means that the expert thinks that biology teachers do not need to use many lessons or time to review the fossil evidence of evolution. It is a direct response to the CoRe question about which curriculum content is least important to review. Another example of a code description is 'low PCK in teachers'; this refers to the fact that a limitation in knowing students' preconceptions about evolution is the low PCK of the biology teachers themselves (the supplementary materials describe all codes). Each of the components' triangles in the $cPCK_{evo}$ was divided according to the number of codes present.

Study design and participants (Study II)

The main part of the present research portrays the use of the $cPCK_{evo}$ created in Study I to describe the development of personal PCK_{evo} among seven female biology teachers not included in the aforementioned community. The study used a qualitative multiple case study methodology (Yin, 2017). This research design is useful for analysing the data

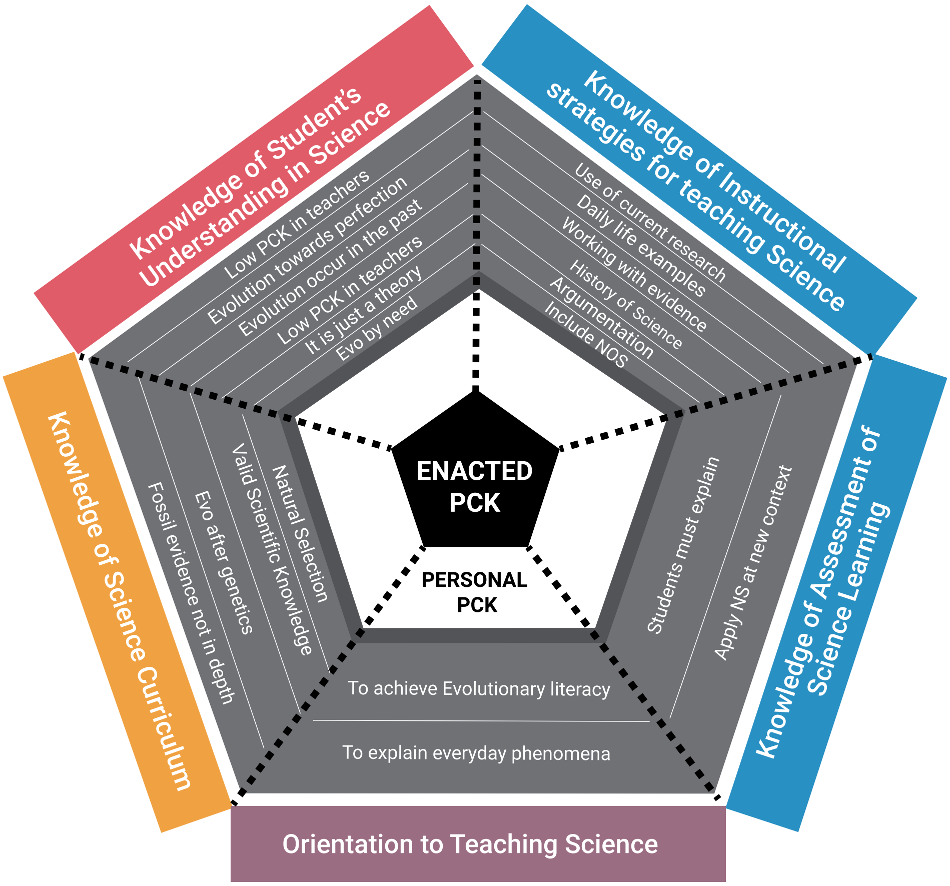

Figure 3. Representation of the collective PCK for evolution after analyzing and synthesising CoRe interviews from six experts in teaching evolution and researching evolution education. The model assumes that the total area of each PCK component is filled with the total number of core ideas on which there is consensus in the community of teachers and researchers.

both within and across situations and can be employed for contrasting results between cases (Yin, 2017). All teachers included in this study participated voluntarily and signed an informed consent form approved by the ethics committee of the university of the researcher responsible for the project. Table 2 provides information about the seven female biology teachers who participated in a PDP about teaching evolution at the high school level that lasted for one semester in 2018, 2019, or 2020. Each researcher met with one teacher to discuss her decisions on what sequence of activities she would implement to teach the evolution unit included in the ninth grade of the Chilean curriculum. The researcher was a non-participant witness who only inquired about the reasons for the planning decisions. This process of conversation has the capacity to make teachers reflect; all teachers had the same opportunity. During this process, the researcher attended all the planning meetings, which were recorded, in person or by Zoom. The CoRe interview also has the capacity to make teachers reflect (Loughran et al., 2012). As the interview was the same for everyone, with the same questions, we

Table 2. Profiles of the seven female biology teachers who participated in the learning study about teaching evolution at high school (B = bachelor's in biology; C = Certificated biology teacher; M = master's in science education. Short PDP experience = Less than one month; Long PDP experience = Between 3 and 6 months).

Teacher pseudonym	Years of teaching experience	Qualifications	Professional Development Program (PDP)	Type of school	Context
Annie	16	B + C + M	Long	Private School	Presential
Francis	5	B + C + M	Long	Private School	Presential
Victoria	7	B + C + M	Long	Public School	Presential
Elizabeth	8	B + C	Long	Private School	Online
Kyara	4	B + C + M	Short	Public school	Online
Brenda	11	B + C	No-exp	Private School	Presential
Alex	11	B + C	No – exp	Private School	Presential

assumed that the changes between pre – and post – for each teacher would be because of the teacher's reflections on planning and/or teaching the lessons. Thus, the steps in this PDP were as follows: (1) the first application of CoRe, (2) lesson plan meetings, (3) conduct the lessons, and (4) the last application of CoRe.

Data collection and analysis

An image of each teacher's PCK_{evo} elements was constructed as the outcome of the content analysis of the two CoRe (Loughran et al., 2012) interviews before and after the instruction. The two CoRe interviews of each teacher were conducted by the same researchers who had experience with this type of interview and in teaching evolution. After transcribing both interviews, a coding process (such as the one carried out with the experts who participated in the creation of cPCK) was performed, including an inductive and deductive process (Miles et al., 2019; Saldaña, 2015). This selective coding process allowed us to carry out systematic organisation with respect to the key concepts and thus to build semantic networks and a PCK map of $pPCK_{evo}$. The total number of codes recognised by each teacher after the consensus process of the two researchers fluctuated between 15 and 28 before and after the lessons. Finally, for each biology teacher, pre – and post-intervention $pPCK_{evo}$ values were compared with those of $cPCK_{evo}$ in a qualitative way to describe the development of $pPCK_{evo}$. The comparison was carried out according to three main characteristics of the $pPCK_{evo}$ map: (i) changes in total area, (ii) changes in map shape, and (iii) changes in code identity. Changes in area refer to the spaces occupied by each of the codes within the triangles of the pentagon. The greater the number of codes, the greater the number of spaces and therefore the larger the area of the pentagon of $pPCK_{evo}$. The change in shape indicates which of the triangles that represent the components are occupied by the different codes. Finally, the identity of the codes was analysed separately since the spaces on the map are filled simply by the presence of the codes, not by the meaning of each one. Identity refers to the definition or meaning of a code. A teacher can have in his or her personal

PCK 7 codes in the pre-intervention and 7 codes in the post-intervention, but their identities can be different. This is why it is another variable that was studied. For example, recognising the preconception of evolution by need is a code that is placed in the component of students' understanding. This is the same as recognising the preconception that evolution is just a theory. Their contribution to pPCK is the same in terms of the number of codes and even the shape because they will be in the same section of the pentagon, but they do not have the same meaning or identity.

Results

Collective PCK_{evo} in Chile

As shown in Figure 3, the final $cPCK_{evo}$ included 20 codes: 2 for the OTS component, 4 for the CuK component, 6 for the KS component, 2 for the KA component, and 6 for the KIS component. Hence, there are two components (KS and KIS) that concentrate on the frequency of codes, while there is less development and consensus on the curriculum component, and even less on the assessment and orientation components.

Regarding the identity of the codes present in the cPCK, the KS component is composed of 5 preconceptions (e.g. it is just a theory) and a limitation about how to work on it (low PCK in evolution). The KIS component includes 6 strategies associated with the use of different contexts, both close to the students and associated with the new epistemological view that they must develop to understand evolution (e.g. NOS). The CuK component encompasses two core ideas (e.g. natural selection), one accessory topic (fossils) and one aspect related to the importance of knowing about genetics before studying evolution. Finally, the KA and OTS components include only two codes focused mostly on asking for explanations and promoting evolutionary literacy, respectively.

Development of PCK_{evo} for Chilean biology teachers

Using the $cPCK_{evo}$ generated through the synthesis of knowledge recognised by experienced biology teachers and scholars in our community as a reference (Figure 3, Table 3), it is possible to analyse whether the $pPCK_{evo}$ of each teacher underwent changes during the lessons implemented and/or the final reflection conducted in the CoRe post. These analyses were carried out according to three main characteristics of the $pPCK_{evo}$ map (area, shape, and code identity). An initial pattern that appears when analysing the pre – and post-test results of each of the seven biology teachers is the increase in the total area of their $pPCK_{evo}$ due to the rise in the number of $cPCK_{evo}$ codes present in each post-CoRe. The following are the numbers of codes distributed across the seven biology teachers: Alex = 0/2; Brenda = 2/4; Kyara = 7/9; Elizabeth = 7/10; Victoria = 7/11; Annie = 7/9; and Francis = 5/11 (Figures 4a and b and Table 3). Because each code has a place in the model diagram or map, an increase in the number of codes implies an increase in the total area of $pPCK_{evo}$. For example, in Figure 4a, the area of Alex's $pPCK_{evo}$ before lessons and the CoRe post is 0 since it does not include any code. In the post $pPCK_{evo}$, however, Alex declares two codes that match the $cPCK_{evo}$, resulting in a small area of $pPCK_{evo}$, represented as two black bands on the SK and KC triangles.

Table 3. List of codes forming the collective PCK of experts and their presence/absence in the Content Representations interviews of the seven biology teachers studied.

	Annie		Francis		Victoria		Elizabeth		Kyara		Brenda		Alex		Total
Codes	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	pre	post	
Orientations to teaching science															
To achieve Evolutionary literacy															
To explain everyday Phenomena					1	1				**1**					3
Knowledge of Students															
Evolution by need		**1**	1	1		**1**	1	1		**1**	1	1	1	1	11
Evolution occurs at individual				**1**								1		**1**	3
Evolution towards perfection				**1**					1	1					3
Evolution occurs in the past	1	1		**1**	1	1			1						6
It is just a theory				**1**	1	1			1	1					5
Low PCKevo in teachers		**1**					1	1							3
Knowledge of Instructional Strategies															
Use of current research	1	1													
Daily life examples			1	1			1	1	1	1	1				9
Working with evidence	1	1		**1**	1	1	1	1							7
History of Science							1	1	1	1					4
Argumentation						**1**									1
Include NOS issues	1	1	1	1	1	1		**1**	1	1					9
Knowledge of Assessment															
Students must Explain				**1**		**1**		**1**				1			4
Apply NS at new context			1	1		**1**			1						4
Curriculum Knowledge															
Natural Selection core idea	1	1		**1**	1	1	1	1							7
Valid Scientific Knowledge core idea					1	1									2
Evolution after genetics	1	1	1				1	1		**1**					6
Fossil evidence not in depth	1	1							1	1				1	5
Total	**7**	**9**	**5**	**11**	**7**	**11**	**7**	**9**	**6**	**8**	**2**	**4**	**0**	**2**	

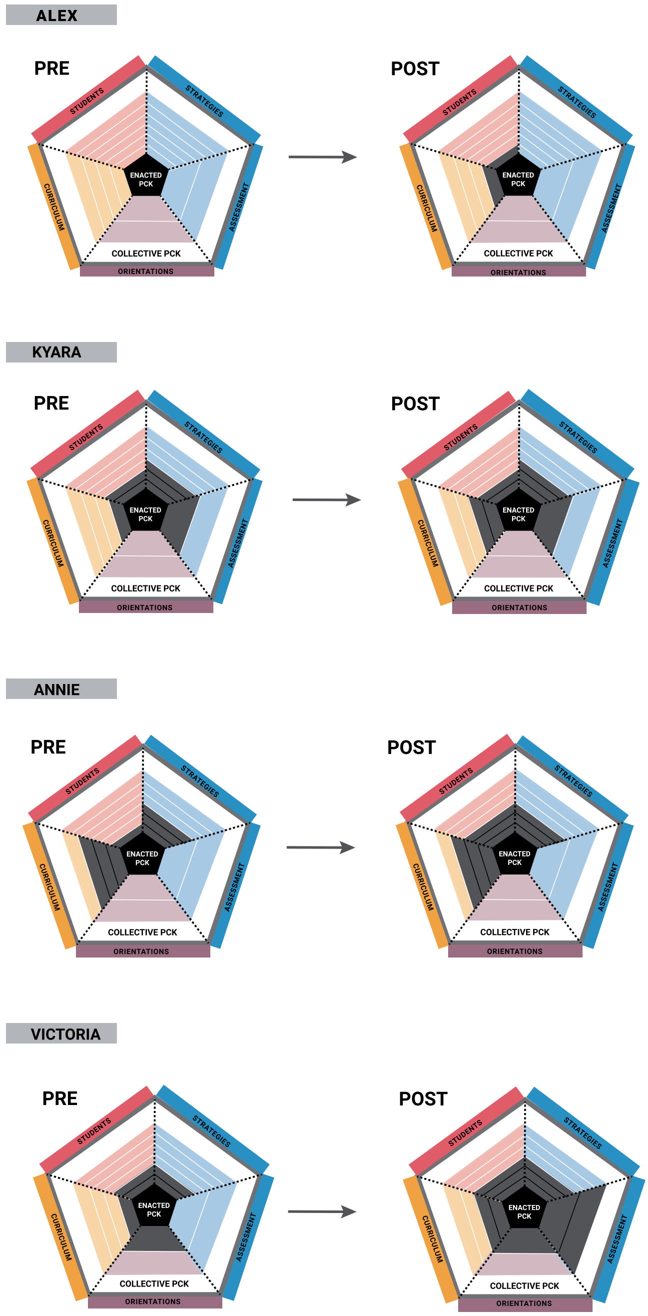

Figure 4. ab. Here is the map or representation of the personal PCK of seven biology teachers before and after their lessons. In each case the change in shape and area is showed. Each triangle represents one of the five components of the Magnusson et al.,' model (1999).

In a very different outcome, Victoria starts with a $pPCK_{evo}$ with 5 codes, which is represented by 5 bands in her $pPCK_{evo}$ space. After lessons and reflection, Victoria increased this area, filling a larger $pPCK_{evo}$ space, and filling it completely in the assessment component.

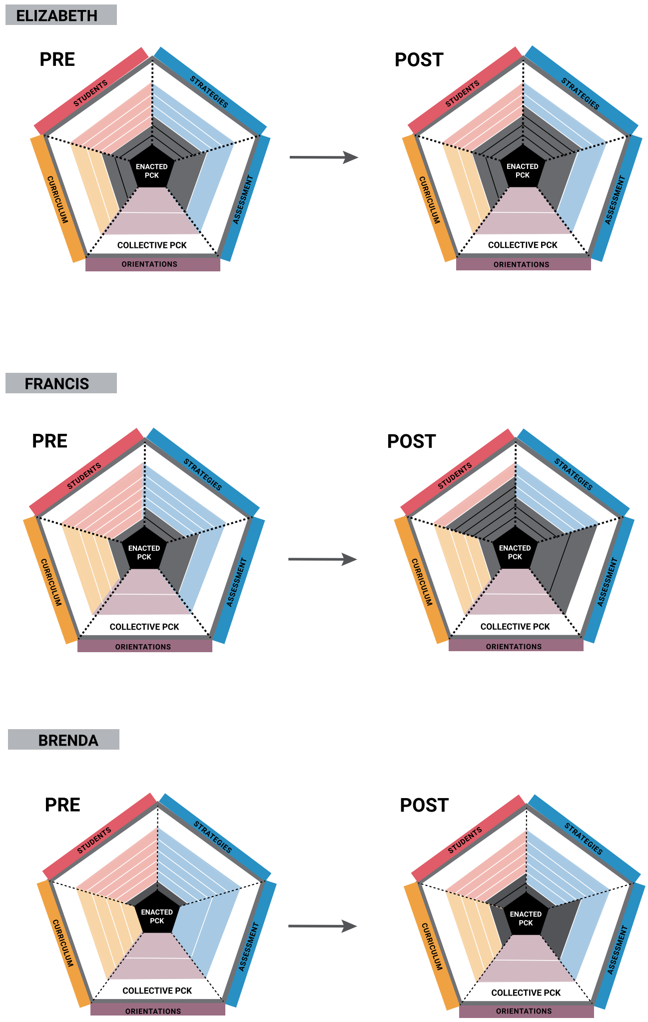

Figure 4. Continued.

In the same vein, it is possible to see a pattern in which teachers with no experience in PDPs for teaching evolution start with small PCK areas (Alex and Brenda). Most of the teachers with more extensive experience tended to have a large $pPCK_{evo}$ at the beginning and the largest improvement in area after the lessons and reflection in the CoRe post (e.g. Victoria, Elizabeth, and Francis) (see Tables 2 and 3).

With respect to the shape of the $pPCK_{evo}$ for each biology teacher, these aspects increased in a predictable way. Only three teachers showed the incorporation of a new PCK component after the lessons (Victoria, Brenda, and Alex). Thus, on most occasions, the shape of the $pPCK_{evo}$ changed only due to the increase in the size of the PCK components that already existed (the same triangle in the map). Most of these changes in shape were due to the $pPCK_{evo}$ being related to the KS and KIS components (Figure 4ab). Interestingly, of the model's five components, the one that was least observed, both before and after the lessons and reflection, is that of orientations. That is, the teaching orientations of female teachers did not coincide with those stated by experts in teaching evolution. This is explained by the fact that most of the biology teachers thought that the main aim of evolution education is focused on the importance of this content for understanding biology in general, but not for making decisions in daily life.

Finally, regarding code identity, some of the $cPCK_{evo}$ concepts that appeared more frequently in the $pPCK_{evo}$ of biology teachers were 'evolution by need' (KS), 'daily life examples', 'include NOS issues', 'working with evidence', (KIS), and 'core ideas about natural selection' (CuK) (Table 3). Importantly, the identity of the codes tended to be maintained between pre – and postintervention. Hence, new codes that appeared after the lessons were added to those already possessed or recognised by a teacher. Some codes that appeared after the lessons were recognised as alternative conceptions about the mechanism of natural selection, such as 'evolution by need' and believing that 'evolution occurs at the individual level', and the assessment strategies about 'students must explain' in relation to mechanisms of natural selection (Table 3).

Discussion

The collective PCK of evolution and the new Mixed Model

This paper makes both theoretical and methodological contributions to the topic of PCK as well as to the issue of understanding and teaching evolution. As for the first matter, we believe that the new Mixed Model, a modification of the RCM of PCK – including the components of Magnusson et al.'s model (1999) – is the main contribution of the study because this involves unifying the most recent PCK model (Carlson & Daehler, 2019) with the most widely used in the literature (Chan & Hume, 2019). Through the map proposed in Figure 2, we have generated a more dynamic model that can clearly represent the different types of PCK (collective, personal, and enacted). More importantly, we present a methodology to describe and evaluate the change in teachers' pPCK in comparison with cPCK created through consensus and collaborative discussions by a group of biology teachers and scholars who are dedicated to teaching evolution (e.g. Cofré et al., 2017; Vergara et al., 2022). This methodology for creating cPCK has much in common with recent proposals (e.g. Buldu & Buldu, 2021; Forsler et al., 2023) on the use of the CoRe protocol to promote reflection and capture teachers' knowledge but differs in that the resulting cPCK is not the product of applying a collective CoRe, but rather due to applying an individual CoRe followed by collective discussions and evaluation. We believe that our work and that of Forsler et al. (2023) are closer to the definition of cPCK given by Carlson and Daehler (2019) as specialised teachers' knowledge that has been articulated and shared among a group of professionals. Other proposals – such as that of Buldu and Buldu (2021), which involved a collective process of reflection on pre-service PCK – depart from the original definition of cPCK due to lack of the participants' classroom experience. The latter proposal can be called *collaborative PCK* instead of collective PCK. The same is true for proposals that focus on the generation of paper and pencil tests to evaluate cPCK from the literature (Irmer et al., 2023). These proposals can be understood more as canonical or theoretical PCK rather than collective PCK. Finally, our cPCK creation process is repeatable for any content and any context (other countries or regions) and can even be repeated in the same context, adding more participants. In other words, we believe that the cPCK generation process is dynamic.

Interestingly, several of the concepts identified in $cPCK_{evo}$ coincide with the suggestions of the research on evolution education (e.g. Cofré et al., 2023; Harms & Reiss, 2019; Ziadie & Andrews, 2018); for example, the recognition of frequent alternative ideas such as evolution by need (Nehm, 2018) and the belief that it is 'just a theory' (McComas, 2018), or the use of strategies such as including NOS, the history of science (HOS) or argumentation (Cofré et al., 2023). This cPCK also includes contextual knowledge, especially that associated with the Chilean curriculum; for example, the challenge of teaching evolution before inheritance in the Chilean curriculum ('evolution after genetics') or the fact that there is an excess of content associated with fossils in national documents ('fossil evidence not in depth'). In our $cPCK_{evo}$, evolution content that appears first (in the ninth grade) rather than aspects of inheritance (in the tenth grade) in the Chilean curriculum is problematic. Although there are examples of research showing understanding of natural selection by very young students (5–8 years old) with no experience in knowing aspects of inheritance (Emmons et al., 2016), biology teachers in Chile seem agree more with the literature that proposes reviewing evolution before genetics (Mead et al., 2017). Furthermore, unlike in other parts of the world (see Deniz & Borgerding, 2018 for a review), the cPCK developed in the Chilean community does not recognise religious aspects as a threat to the teaching or understanding of evolution, but $cPCK_{evo}$ recognises the incorporation of the NOS as a crucial aspect of teaching, which is consistent with what has been described in the literature (McComas, 2018; Scharmann, 2018).

Describing the development of $pPCK_{evo}$ in relation to $cPCK_{evo}$

The use of the modified RCM model allowed us to discern patterns widely described in PCK research using Magnusson's or Park's model; for example, there are more developed components in teachers, such as knowledge of students' understanding, and less developed ones, such as knowledge of the assessment of science learning (Park & Chen, 2012; Reynolds & Park, 2021). In the case of evolution-based content, we found that the curriculum component is much more contextualised than teaching strategies or student learning, which rely more on canonical or research-based knowledge (Fischer et al., 2021; Hartelt et al., 2022; Sickel & Friedrichsen, 2013; Ziadie & Andrews, 2018).

We also incorporated one of the most interesting aspects of the RCM by comparing the cPCK with the personal PCK of different teachers in a specific subject. This could spur further research in this area, which has been scarce since RCM was initially proposed (see Behling et al., 2022; Cooper et al., 2022; and some chapters in Hume et al., 2019). If we incorporate cPCK concepts to measure participating teachers' PCK development, several developmental pathways can be hypothesised. First, all teachers develop their PCK by reflecting on their practice, but those with less experience in PDP about evolution start with less development compared to teachers with more professional development experience. Hence, some professional development pathways proposed in the literature (Becerra et al., 2023; Cofré et al., 2017) can lead to the cultivation of $pPCK_{evo}$ that coincides with that proposed in the literature on teaching and learning evolution (Deniz & Borgerding, 2018; Harms & Reiss, 2019).

Limitations

As with any new methodological or theoretical proposal, this study has several limitations. First, we conducted this study essentially based on evidence of personal and not enacted PCK; as such, the results should be interpreted with caution. Another challenge for the model (which we did not consider) is the possibility of recognising the interaction between PCK components, which has been a very fruitful line of research (Park & Chen, 2012; Reynolds & Park, 2021). However, as this line of research has focused mainly on the study of PCK in action or enacted, we believe that both models can be complementary. The study of ePCK could be performed using the Park and Chen (2012) model and its mapping methodology, and studies focusing on the study of pPCK and cPCK could be carried out using the modified model presented here (see also Forsler et al., 2023; Irmer et al., 2023). In addition, the fact that the $cPCK_{evo}$ was created with only 6 experts may be a drawback. However, we believe that the methodology used allows the impact of this limitation to be mitigated in the future. We believe that any cPCK should be taken as a temporary or provisional proposal since the curriculum changes over time, as do the contexts and the students. Therefore, in the future, this $cPCK_{evo}$ model cannot only change as new experts are included in its creation but must also evolve to address new challenges.

Implications and future research

Our results have multiple implications for the research on PCK in general and for the study of PCK_{evo} in particular. First, we used a modified version of RCM, which includes other teachers' knowledge and beliefs, but we did not study the relationship between this knowledge and PCK. One aspect that can be examined in the future is how this new version of the RCM can visualise the relationship with other types of teachers' knowledge, especially SMK. Studies conducted in the past ten years have shown a complex relationship between SMK and some components of PCK (Kind & Chan, 2019; Neumann et al., 2018; Rollnick, 2017), especially students' knowledge of learning (Hartelt et al., 2022; Lucero et al., 2017). As mentioned above, future research should explore whether this new Mixed Model can also be useful for studying ePCK and its relationship with the other realms of PCK. In addition, we have described here a clear, replicable way to obtain cPCK for a particular kind of content, which can be repeated in other contexts for the same purpose or even for inter-context comparison (between countries or regions).

Conclusions

In this research, we have demonstrated that it is possible to describe teachers' knowledge development by comparing their pPCK with the cPCK of a community of biology teachers and science educators. Our Mixed Model, as it combines aspects of the two most important models in the literature – Magnusson et al.'s model (1999) and the RCM (Carlson & Daehler, 2019) – allows many doors to be opened to investigate different ways of understanding PCK development and modelling.

Finally, as for the topic of teaching evolution, we have described for the first time the cPCK of a community of biology teachers in a South American country, in which aspects of canonical knowledge from the literature, as well as local experience, seem to blend well together. By comparing this cPCK with each of the pPCKs at different times, we have found that it is always possible to develop pPCK, although this growth is usually derived from the knowledge that already exists in each teacher. Multiple factors emerge as possible filters or catalysts between cPCK and pPCK, including professional development experience.

Ethical statement

The Pontificia Universidad Católica de Valparaíso research bioethics committee board approved the research procedures included in the project FONDECYT 1211920.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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