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From conceptual foundations to enacted PCK: a mixed-methods study with primary teachers teaching the human body

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ABSTRACT

Pedagogical Content Knowledge (PCK) represents a core component of teachers' professional knowledge and one of the strongest predictors of effective science instruction. This study examines how teachers' Conceptual Knowledge (CK) relates to both their personal and enacted PCK among 13 in-service primary school teachers teaching the human body. An explanatory sequential mixed-methods design was employed, combining a CK test, an analytic PCK rubric, and pre- and post-lesson interviews supported by classroom video recordings. Results revealed a low correlation between CK and PCK, suggesting that they are distinct yet interrelated constructs. However, a functional conceptual threshold was identified, beyond which teachers were able to enact more coherent and scientifically grounded PCK. The qualitative analysis uncovered different patterns of CK–PCK articulation, ranging from routine-based strategies to reflective practices aimed at promoting students' conceptual understanding. These findings reinforce that PCK develops not only through disciplinary mastery but also through sustained reflection and engagement in authentic teaching contexts. Implications are discussed for both preservice and in-service teacher education, highlighting the importance of integrating content learning with didactic analysis experiences that support the development and enactment of PCK across scientific topics and classroom situations.

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Pedagogical Content Knowledge (PCK); Conceptual Knowledge (CK); primary teachers

Introduction

Pedagogical Content Knowledge (PCK) refers to the knowledge teachers use to transform disciplinary content into meaningful learning opportunities (Shulman, 1987). It encompasses not only what teachers know but also how they act on that knowledge and the

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reasoning that guides their decisions (Baxter & Lederman, 1999). PCK develops dynamically through planning, instruction, and reflection (Park & Oliver, 2008), and has been recognised as a core component of teacher professionalism and effective science teaching (Magnusson et al., 1999; Shulman, 2015; Vergara et al. 2024).

Despite its centrality, PCK is rarely taught explicitly in initial teacher education. Research has produced diverse frameworks and assessment approaches (Henze & van Driel, 2015), yet most studies have focused on secondary teachers. As a result, the PCK of primary teachers – who introduce science during the most formative years – remains comparatively understudied.

The relationship between PCK and Conceptual Knowledge (CK) is particularly relevant in this context. Although strong CK does not automatically lead to effective teaching, a minimum conceptual foundation appears necessary for functional PCK to emerge (Magnusson et al., 1999; van Driel et al., 2014). This requirement is critical for primary teachers, who often display lower CK than their secondary counterparts (Appleton, 2003; Roth, 2014), constraining their ability to interpret scientific phenomena and support causal reasoning (Van Driel et al., 1998). International reviews consistently report a dual challenge in primary science teaching: limited disciplinary mastery and insufficient opportunities to develop subject-specific pedagogy (Roth, 2014).

Empirical evidence on how CK and PCK interact in practising teachers is scarce. Existing research has largely focused on preservice teachers (Beyer & Davis, 2012; Nilsson & Loughran, 2012) and prioritised declarative PCK, offering little insight into how knowledge is enacted in classroom practice. Consequently, a persistent gap remains in understanding how primary teachers integrate conceptual and pedagogical knowledge when planning, teaching, and reflecting on science topics.

In Chile, this issue is particularly salient, as primary teacher education programmes devote limited curricular time to science-specific pedagogy and opportunities for developing pedagogical content knowledge, with an emphasis on general pedagogy over subject-specific teaching (Cofré et al., 2015). This limits the possibility of building strong foundations for science learning in the early grades, when attitudes and understandings toward science are first shaped (Nilsson, 2017). Understanding the relationship between CK and PCK among in-service primary teachers therefore constitutes both an academic and a professional priority.

From this context, the present study sought to address the following research question:

What is the relationship between the conceptual knowledge (CK) and the pedagogical content knowledge (PCK) of in-service primary school teachers when teaching a specific topic of the human body?

To address this question, the study pursued four complementary objectives:

(1) To develop and validate a PCK rubric that integrated both declarative and procedural sources;
(2) To quantitatively examine the relationship between CK and PCK, identifying whether teachers with higher CK exhibit higher levels of PCK and whether a minimum CK threshold exists for functional pedagogical performance;
(3) To qualitatively analyse teachers' pedagogical decisions – before, during, and after teaching – exploring how they articulate their PCK across different levels of conceptual knowledge; and

(4) To integrate quantitative and qualitative findings in order to characterize how CK and PCK interact in teaching practice and to derive implications for initial and continuing teacher education.

Literature review

This section synthesises previous research on pedagogical content knowledge (PCK), conceptual knowledge (CK), and their relationship in primary science education, with particular attention to the challenges associated with teaching the human body.

PCK in science education

A broader field perspective shows sustained growth in PCK research, predominantly in secondary science and mathematics. A recent field synthesis (Santibáñez et al., 2025a) confirmed limited attention to primary schooling and to designs integrating both personal and enacted PCK. This underscores the need for studies drawing on multiple data sources (e.g. lesson plans, interviews, classroom observations) and analysing teacher knowledge within specific curriculum topics (Chan et al., 2019; Kirschner et al., 2015; Park & Oliver, 2008).

Conceptual knowledge in primary science

For primary teachers, the relationship between CK and PCK is especially challenging. Many report limited science backgrounds and low confidence, often rooted in negative school experiences (Mensah, 2016). Their conceptual difficulties may mirror those of pupils (Hanuscin et al., 2018), and low self-efficacy can lead to avoiding science teaching (Appleton, 2006). Despite efforts to improve preservice and in-service programmes, substantial gaps persist (Bullough & Smith, 2016; Lewis, 2019). In Chile, for example, only about 7% of coursework in primary teacher education is devoted to natural sciences – typically two disciplinary modules and one didactics course (Vergara & Cofré, 2008).

Evidence from a recent systematic review (Santibáñez et al., 2025b) shows that, despite limited preparation, primary teachers can transfer elements of PCK across curriculum areas, adapting knowledge structures and strategies to new domains. This suggests that strengthening CK relies not only on coursework but also on pedagogical reconstruction and accumulated experience. Yet findings on how teachers' CK influences pupil learning remain inconsistent, raising an important question in the literature: what level of CK is sufficient for functional PCK in science teaching?

The CK–PCK relationship

The relationship between CK and PCK has been widely examined. CK is generally viewed as a necessary – though insufficient – basis for PCK development (Appleton, 2006; Nilsson, 2008): teachers need a sound grasp of scientific ideas to recognise pupils' alternative conceptions (Hanuscin et al., 2018). Yet high CK does not guarantee PCK, as teaching requires mobilising understanding in didactically productive ways (Lin, 2017). Some studies suggest the existence of a minimum CK threshold supporting the emergence of PCK (van Driel et al., 2014), although its value may vary by context and topic.

Research in secondary education has clarified aspects of this relationship, whereas studies with in-service primary teachers remain limited (Meschede et al., 2017). Among primary teachers, CK and PCK seem to interact synergistically during early professional stages (Lee & Luft, 2008), with novices gradually integrating conceptual understanding with general strategies and moving toward topic-specific reasoning (Nilsson, 2008). This progression underscores the dynamic nature of PCK and its co-evolution with disciplinary understanding and reflective practice.

The Chilean context

These challenges become particularly visible in specific national contexts. In Chile, concerns about primary science teaching are closely linked to limitations in initial teacher education, particularly reduced opportunities to develop PCK. Natural science coursework has historically occupied a small proportion of preparation programmes: Cofré et al. (2015) found that less than 7% of courses addressed natural sciences, typically through only one or two disciplinary modules and a single didactics course. The two disciplinary modules focused on strengthening teachers' CK, while the didactics course addressed the development of PCK. This imbalance constrains both CK development and opportunities to integrate knowledge into practice.

National assessments reflect these limitations, as many graduates report feeling unprepared to teach science (Centro de Perfeccionamiento, Experimentación e Investigaciones Pedagógicas [CPEIP], 2020). Regulatory frameworks, such as the Standards for Performance in Initial Teacher Education (CPEIP, 2022), position PCK as central to pedagogical preparation, yet implementation varies considerably across institutions.

The challenge is especially acute in primary schooling, where teachers act as generalists. Weak disciplinary backgrounds limit their ability to interpret curriculum goals, respond to learners' ideas and build a coherent PCK base – issues also highlighted internationally (Nilsson, 2017). Strengthening CK and its pedagogical transformation is therefore a key priority.

Within this context, the relationship between CK and PCK among in-service primary teachers remains underexplored. Such approaches, combining objective measures of CK with qualitative analyses of enacted PCK, may contribute to informing programme design and advancing understanding of science teacher professionalism.

Teaching the human body

The human body is a central axis of the primary science curriculum, integrating ideas from health, biology and the study of living systems. Yet research on its teaching is less extensive than in other biological domains (Cofré et al., 2023). Scholars emphasise the need to address it as a complex system rather than as a collection of isolated 'apparatuses' (Ben Zvi Assaraf & Snapir, 2018).

Teaching this topic presents multiple challenges. Pupils hold persistent alternative conceptions about organ location and function (Allen, 2010; Driver, 1994) and often adopt teleological explanations (Jaakkola & Slaughter, 2002). Difficulties in understanding interactions – particularly among circulatory, respiratory and digestive subsystems – are well documented (Ben Zvi Assaraf et al., 2013) and may be reinforced by simplified textbook representations (Carvalho et al., 2004).

These challenges require teachers to mobilise substantive CK and PCK through modelling, practical activities and conceptual discussion. Yet research shows that teachers often rely on engaging but conceptually limited tasks (Appleton, 2006). Although the human body is familiar and tangible, its teaching demands strong integration of disciplinary and pedagogical knowledge.

As one of the 'big ideas of science', it offers a rich context for examining how teachers translate complexity into meaningful learning opportunities (Harlen, 2010). In the literature, this topic has been used as a representative case for analysing personal and enacted PCK, offering insight into how pedagogical decisions evolve when CK is limited or fragmented.

Taken together, these strands of research highlight the complexity of the CK–PCK relationship and the need for integrative approaches that account for both conceptual understanding and pedagogical reasoning. The following section outlines the theoretical framework guiding this study.

Theoretical framework

Building on this body of research, the present study adopts a theoretical framework that conceptualises PCK and CK as dynamic and interrelated forms of teacher knowledge, emphasising their articulation in practice through personal and enacted dimensions.

Conceptualising PCK and CK

Building on Shulman's (1986, 1987) initial conceptualisation, PCK has been further developed to account for how teachers transform disciplinary content into teachable, topic-specific learning opportunities. It encompasses what teachers know, how they apply that knowledge in practice, and the reasoning that supports their decisions (Baxter & Lederman, 1999). Within science education, PCK has become a central construct for interpreting instructional quality, informed initially by Magnusson et al.'s (1999) model and later reframed through transformative and integrative perspectives (Gess-Newsome, 1999; Rollnick et al., 2008). Despite its widespread use, PCK has been characterised by conceptual ambiguity and lack of consensus regarding its structure and components (Kind, 2009).

Conceptual Knowledge (CK) refers to the depth, organisation and integration of ideas underpinning understanding within a scientific domain (Zeidler, 2002). It entails linking concepts meaningfully, recognising hierarchical relations and applying them to interpret phenomena (Biggs, 1992/2005).

Although disciplinary understanding is viewed as a prerequisite for PCK development (Nixon et al., 2019; van Driel et al., 2014), the relationship is increasingly understood as bidirectional, with engagement in PCK reorganising and strengthening CK (Roth, 2014). This reciprocal relationship aligns with more recent views of PCK as an emergent construct, arising through dynamic interactions between CK, pedagogical knowledge (PK), and classroom practice (Kind & Chan, 2019).

Because PCK is topic-specific, knowledge developed for one domain does not automatically transfer to another: a teacher skilled in teaching the human body may function as a novice in ecology (Hanuscin et al., 2018). PCK arises through the situated interplay between topic-specific CK, pupils' ideas and contextual conditions. Primary teachers therefore face the challenge of constructing and enacting PCK across multiple areas simultaneously (Appleton, 2006), contributing to the fragmentation seen in their repertoires.

Several studies show that teachers often compensate for disciplinary uncertainty by developing pragmatic forms of PCK based on materials and 'activities that work' (Appleton, 2006; Smith, 1999). Although instrumental, this knowledge supports instruction under conceptual constraints. Some scholars conceptualise this process as epistemological reconstruction, whereby teachers progressively reinterpret disciplinary knowledge through practice and reflection (Porlán Ariza, 2018). These processes strengthen in collaborative contexts where teachers share and adapt didactic principles (Nilsson, 2008).

In sum, the CK–PCK relationship follows a developmental trajectory in which conceptual mastery offers a foundation, yet PCK emerges through transforming that knowledge into action. This perspective guides the present study: examining a potential CK threshold linked to PCK levels and exploring how teachers mobilise knowledge to support pupils' understanding.

Personal and enacted PCK

Recent developments – particularly the Refined Consensus Model – conceptualise PCK as dynamic, context-sensitive and inherently topic-specific (Carlson & Daehler, 2019). This framework distinguishes personal PCK, reflected in teachers' articulated rationales, from enacted PCK, visible in their instructional decisions (Park & Chen, 2012; Schneider & Plasman, 2011), a distinction essential for examining how teachers mediate scientific ideas.

Taken together, contemporary models portray PCK as situated and developmental, becoming visible in both teachers' articulated reasoning and their in-action decisions. This distinction between personal and enacted PCK provides a central analytical lens for examining how teachers mobilise conceptual knowledge in practice.

Measuring PCK in Practice

PCK has been examined through diverse tools and methodological approaches. Measurement efforts have traditionally drawn on Magnusson et al.'s (1999) model, from which several analytical adaptations have emerged to distinguish dimensions such as curriculum knowledge, student understanding, instructional strategies and assessment (Park et al., 2011; van Driel et al., 2014).

Developing valid measures remains complex. Many instruments focus on declarative PCK – what teachers articulate about planning or preferred instruction – but this represents only part of the construct, as PCK becomes visible and transforms in the classroom (Hanuscin et al., 2018). Recent research therefore differentiates between personal and enacted PCK, consistent with the Refined Consensus Model (Carlson & Daehler, 2019).

Analytical rubrics have become a productive strategy for integrating these dimensions. Building on Gardner and Gess-Newsome's (2011) work, rubrics enable qualitative evidence to be translated into comparable scores while retaining close ties to practice. Their flexibility and reliability have led to widespread adoption (Chan et al., 2019), although many rubric-based studies rely on a single data source and emphasise only selected components of PCK. Scholars therefore recommend triangulating sources – including interviews and classroom observations – to capture both declarative and procedural aspects of PCK (Morrison & Luttenegger, 2015).

In line with these recommendations, this study employs a mixed measurement strategy that integrates rubrics, interviews and video records to examine PCK in its declarative and enacted forms.

Analytical framework and study rationale

Within this framework, PCK in science is examined as a dynamic, situated form of knowledge that becomes visible both in teachers' articulated rationales and in their classroom decisions. Contemporary models portray PCK as emerging from the interaction between conceptual understanding and pedagogical reasoning. Yet most empirical studies have examined PCK primarily through its declarative dimension. Bibliometric and systematic review evidence (Santibáñez et al., 2025a) highlights the scarce attention to how CK and PCK interact within actual teaching practice, particularly in primary education.

The relationships outlined above are synthesised in Figure 1, which represents the conceptual framework guiding this study. The model highlights the role of CK as a

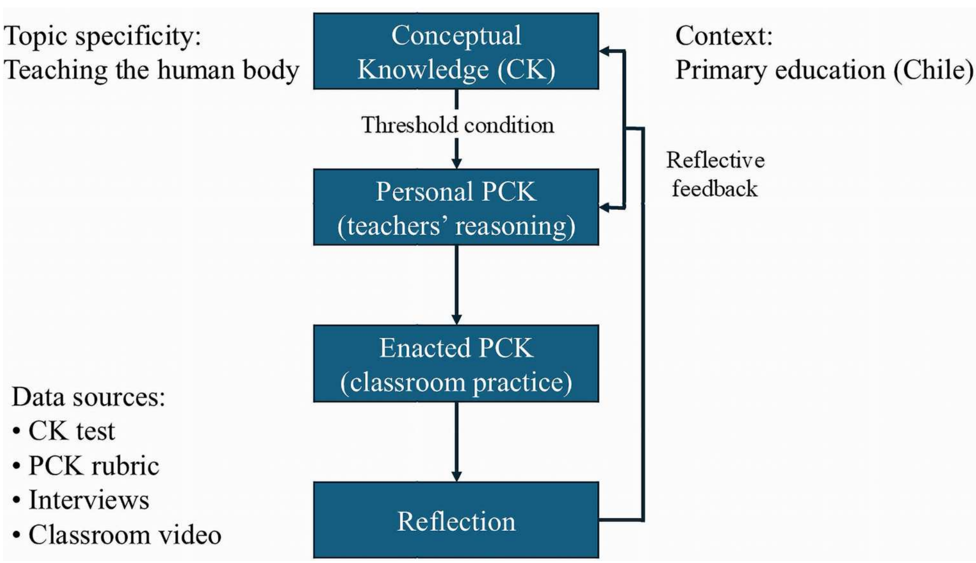

Figure 1. Conceptual framework of the study. The model represents the relationship between CK and PCK, highlighting a threshold condition for PCK emergence. It distinguishes between personal PCK (teachers' reasoning) and enacted PCK (classroom practice), connected through reflective practice. The framework is situated within a topic-specific context (teaching the human body).

condition for the emergence of PCK, and distinguishes between its personal and enacted dimensions, connected through reflective practice.

Methodology

An explanatory sequential mixed-methods design was employed, integrating objective measures of CK and PCK with qualitative analyses of their enactment. This design supports the examination of how teachers' knowledge is expressed across personal, enacted, and reflective dimensions.

Participants

A total of 110 Chilean primary teachers were invited to participate via an electronic form explaining the study and requesting consent to video-record a lesson on the human body, a topic in the national fifth-grade science curriculum. Thirteen teachers (10 women, 3 men) from schools in central Chile agreed to participate voluntarily. Inclusion criteria were: (a) teaching the human body in fifth grade, (b) permitting audiovisual recording, and (c) participating in pre- and post-observation interviews. This sample was considered adequate for an explanatory mixed-methods design involving exploratory statistical analysis and qualitative comparison.

Data collection

Two dimensions were examined: Conceptual Knowledge (CK) and Pedagogical Content Knowledge (PCK). Each teacher (a) completed a CK test, (b) planned a lesson on the human body, (c) was video-recorded during its implementation, and (d) participated in pre- and post-observation interviews. Evidence from these sources was integrated using an analytical PCK rubric (Gardner & Gess-Newsome, 2011; Park et al., 2011) aligned with the components proposed by Magnusson et al. (1999): knowledge of curriculum, instructional strategies, assessment, and student understanding.

Instruments

Conceptual knowledge test

The CK test initially included 25 multiple-choice items on human anatomy and physiology, aligned with national standards for primary teacher education and the official primary science curriculum. Distractors reflected well-documented alternative conceptions (Driver, 1994). Expert review ensured curricular alignment and appropriate difficulty. Following administration, three items were removed because they were answered correctly by all participants and therefore showed no discriminative capacity. A subsequent item analysis was conducted to examine internal consistency, and additional items with low contributions to reliability were excluded. The final version of the instrument included 16 items. Reliability was satisfactory (Cronbach's alpha = .719; KR-21 > .70). The total score (0–16) served as the CK indicator.

PCK assessment

PCK was assessed using three complementary sources: (a) a personal reflection guide based on the PRIME PCK Reflection (Gardner & Gess-Newsome, 2011), (b) pre- and post-observation interviews, and (c) video-recorded lessons.

Information was synthesised through a 15-indicator rubric across four performance levels (0–3), with a maximum score of 45. The rubric was theoretically grounded in established models of PCK (e.g. Magnusson et al., 1999; Park et al., 2011) and adapted from the PRIME PCK Reflection framework. Two additional indicators were incorporated to capture (a) teachers' ability to sustain alignment with the intended curricular objective during instruction and (b) their responsiveness to students' ideas during lesson enactment.

The rubric was reviewed by two experts in teacher education; 20% of cases were double-coded, achieving full inter-rater agreement.

The full CK test and PCK rubric are provided as Supplementary Material.

PCK reflection guide

Written reflections and interview responses probed teachers' decision-making and rationales related to lesson planning, implementation, and assessment. Questions were derived from the components of Magnusson's model. Post-observation interviews explored the reasoning underlying observed actions and were fully audio-recorded, then selectively transcribed for thematic coding.

Video analysis

Classroom recordings were analysed with a focus on content mediation, teacher–student interactions, and evidence of student understanding. These observations informed the 'Implementation' section of the PCK rubric and guided subsequent interview prompts.

Data analysis

Quantitative analysis

To examine the relationship between CK and PCK, CK scores were grouped into three levels (low, medium, high). A Kruskal–Wallis test was used to determine differences in PCK across these groups, followed by post-hoc comparisons to identify where significant contrasts occurred. A Pearson correlation was then computed to assess the linear independence between the two variables. Together, these analyses enabled the exploration of a potential functional CK threshold – that is, the point at which conceptual knowledge begins to support more integrated forms of PCK.

Qualitative analysis

Interview data and classroom recordings were analysed using a thematic–comparative approach (Braun & Clarke, 2019) to identify patterns in the articulation between CK and PCK. The unit of analysis comprised discourse segments or classroom episodes reflecting pedagogical decisions related to content.

Analysis proceeded in three stages:

(1) Initial coding, informed by the four components of Magnusson's model and by the distinction between personal and enacted PCK (Carlson & Daehler, 2019).
(2) Axial grouping, enabling comparison across CK levels (low, medium, high) and the description of PCK progression within each group.
(3) Narrative synthesis, integrating emerging categories around four axes: CK–PCK articulation, personal PCK, enacted PCK, and pedagogical reflection–projection.

Credibility was strengthened through triangulation of data sources (interviews, videos, reflections) and inter-coder validation. Final interpretations were reviewed by an external expert in teacher education to ensure coherence with the theoretical framework.

Ethics

All participants provided informed consent. Video recordings and transcripts were anonymised using pseudonyms and stored in a secure repository in accordance with Chilean data-protection legislation.

Results

Quantitative results

General patterns

Scores on the human body CK test ranged from 5 to 16 points (M = 10). Only one teacher attained the maximum score, while five scored 8 or below. PCK scores ranged from 17 to 35 (M = 25). Relative to their maximum possible scores (16 and 45), CK performance was slightly stronger than PCK performance (Figure 2).

Test reliability

Following item analysis, the 16-item version of the CK test showed acceptable reliability (Cronbach's alpha = .719; KR-21 > .70). Only these 16 items were used in the statistical analyses.

Kruskal–wallis test

A Kruskal–Wallis test (Jamovi v.2.2) revealed no significant differences in PCK across the three CK groups ($\chi^2 = 3.25$, $p > .05$). Pairwise comparisons also yielded no significant contrasts (Tables 1 and 2). The group mean plot (Figure 3) shows considerable within-group variability, precluding clear trends.

Correlation analysis

A low correlation was observed between CK and PCK ($r = .42$, $p > .05$). Teachers with higher CK did not consistently show higher PCK; however, all teachers with low CK displayed low PCK (Figure 4).

Table 1. Kruskal–Wallis Test Comparing PCK Across CK Groups.

Variable	χ^2	df	p	ε^2
PCK	3.25	2	0.197	0.271

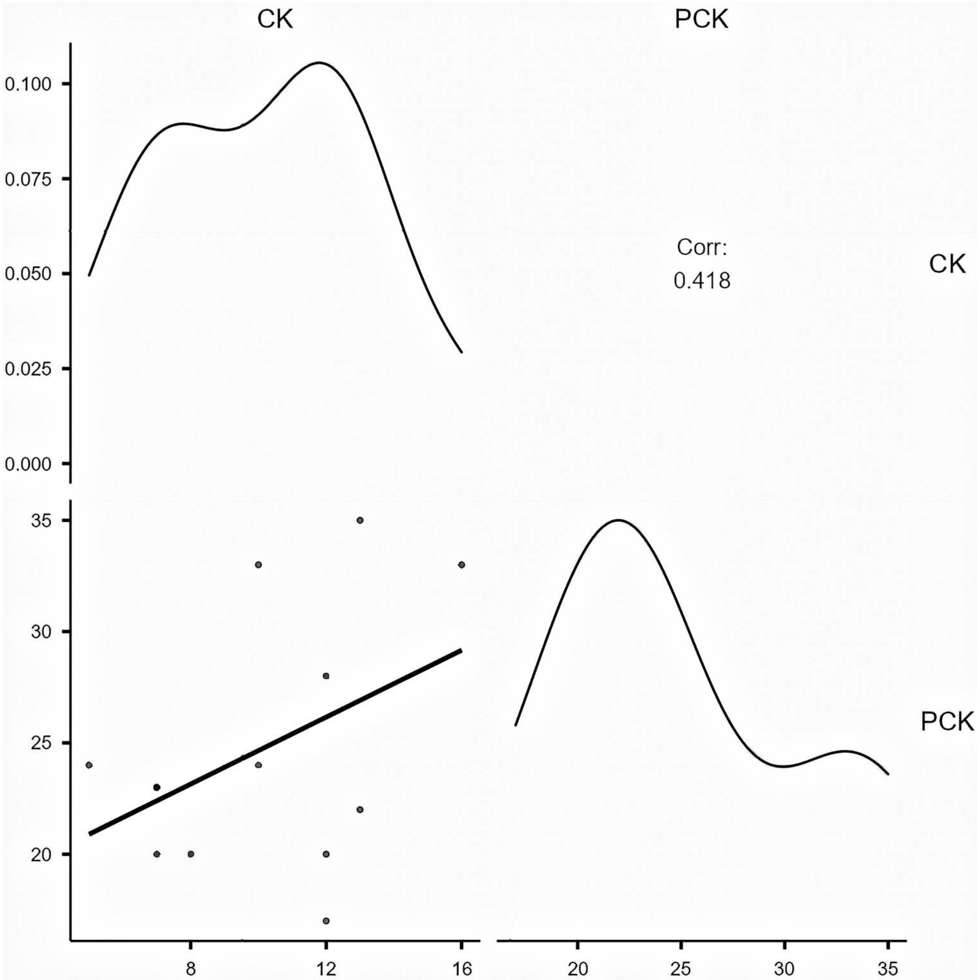

Figure 2. Relationship between CK and PCK. The scatter plot (bottom left) shows individual teacher scores with the regression line indicating the overall trend. The plots on the diagonal represent the distribution of CK (top left) and PCK (bottom right) scores. The value in the upper right panel indicates the correlation between both variables ($r = .418$).

Qualitative results

CK–PCK articulation

Three progressive modes of CK–PCK integration were identified, reflecting differences in conceptual mastery and pedagogical sophistication.

Table 2. Pairwise comparisons among CK levels.

Comparison	W	*p*
Low CK – Medium CK	0.178	0.991
Low CK – High CK	2.445	0.195
Medium CK – High CK	1.848	0.392

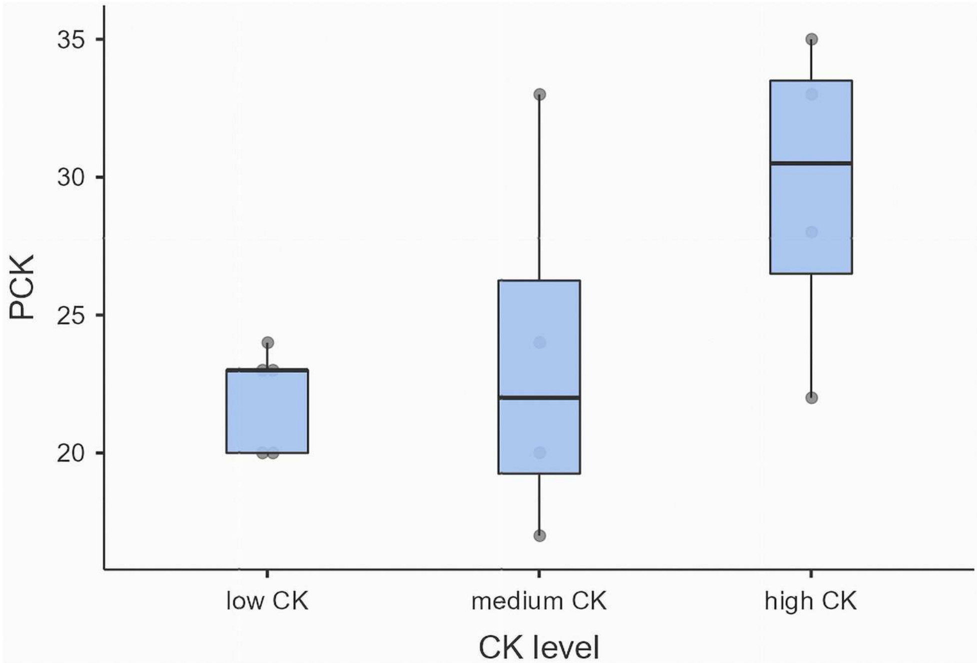

Figure 3. Distribution of PCK by CK level. Variability prevents significant group differences.

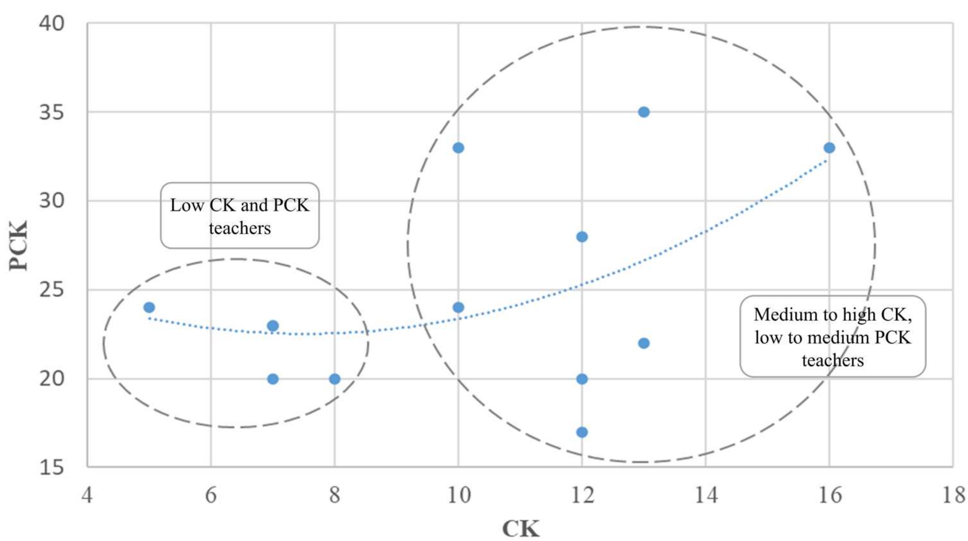

Figure 4. Relationship between CK and PCK, showing two clusters: low CK/low PCK, and medium to high CK with more varied PCK. Note: Two cases share identical CK and PCK scores and therefore overlap in the graphical representation.

Low CK – Compensatory functional PCK. Teachers compensate for limited disciplinary understanding through the use of concrete resources and sensory representations. As Patricia described, 'I placed cookies on their desks … what we experienced was how the digestive process works … they could, in a way, feel the process,' while Ana reported using 'gloves, paint, and some modelling clay … the glove to simulate the intestinal villi, to make it more concrete so children could actually see what they are.' Their explanations emphasise motivation and perceptual accessibility rather than causal reasoning. CK acts as a constraint: explanations remain superficial and centred on 'making phenomena tangible' rather than scientifically grounded.

Intermediate CK – Emerging conceptual–pedagogical integration. Teachers begin to link biological concepts with everyday experiences, activating causal reasoning and using multiple representations. As Karina explained, 'students tend to mix together different ideas they have heard in order to make sense of what I am asking, and from there we try to identify the differences and the processes involved,' using these initial conceptions as a starting point for instruction. Javier, for example, connects alveolar structure with smoking, asking: 'If the alveolus cannot do its job … what happens to the oxygen we need?' Here, CK organises instructional decisions, supporting a procedural PCK that blends conceptualisation, dialogue, and experimentation.

High CK – Transformative and reflective PCK. Teachers with strong CK reconstruct disciplinary knowledge to guide learning. Doris warns that models 'can lead to conceptual error if not analysed,' showing epistemological awareness; Cristian designs experiments to provoke cognitive conflict and promote inductive reasoning, for example by posing a problem in which 'they have to help two children in a supermarket … one cannot eat lipids and the other cannot eat carbohydrates,' encouraging students to formulate predictions and 'then reach their own conclusions.' PCK becomes a reflective transposition competence, using science as an object of inquiry.

Overall progression. Teachers with low CK rely on concreteness; those with intermediate CK integrate scientific ideas into explanations; those with high CK transform CK into a resource for pedagogical reflection. PCK develops when CK becomes an instrument for mediating understanding rather than a repository of strategies.

Personal PCK

Personal PCK – teachers' purposes, beliefs and decision-making – showed a progression from experiential to reflective orientations. However, this evolution was not strictly linear: within the intermediate CK group, both sophisticated and more superficial forms of PCK coexisted, indicating diverse trajectories in the pedagogical appropriation of scientific knowledge.

Low CK – Intuitive, relational PCK. Teachers with low CK prioritised motivation, relevance and affective engagement. Patricia used a 'cookie activity' to shift students' mindsets so they 'realise it really happens.' Her aim was awareness rather than conceptual precision. In a similar vein, Elena asked students 'in which structure the substances are being formed' when working with a model of the digestive system, reflecting an attempt to link representations and processes, but also revealing imprecision in the underlying conceptual understanding. Decisions emerged from relational and experiential orientations rather than explicit content analysis, yet maintained a clear formative intent.

Intermediate CK – Heterogeneous personal PCK. Within the intermediate CK group, PCK presented a heterogeneous configuration, characterised by the coexistence of more integrated and more descriptive or experience-based approaches to teaching.

Some teachers – such as Kathy and Javier – integrated CK with pedagogical decision-making coherently. Kathy connected digestion with nutritional disorders and used videos 'with simple language and humour,' recognising the importance of emotional engagement. Javier used pulmonary physiology to promote causal reasoning and ethical reflection: 'If the alveolus cannot do its job … what happens to the oxygen we need?' Other teachers showed more empirical and descriptive forms of PCK. Karina focused on distinguishing terms, while Marcela grounded instruction in students' everyday bodily experiences, explaining that she now tries to 'find meaning in learning – not for me, but for them.' This variation indicates that PCK development relies not only on disciplinary understanding but on teachers' capacity to transform science into meaningful learning through reflection and justification.

High CK – Metareflective personal PCK. Among teachers with higher CK, personal PCK adopted a metareflective character, understood as the capacity to critically examine and intentionally transform one's own pedagogical decisions in light of disciplinary and epistemological considerations. Cristian combined modelling, experimentation and contextual problem-solving, emphasising student autonomy: 'I've tried everything from lecturing to units where I've barely explained any content.' Doris highlighted the epistemological dimension of scientific models, noting that 'they can lead to conceptual errors if not discussed.' Both viewed teaching as investigative work, deliberately integrating disciplinary understanding with children's thinking.

Overall, personal PCK unfolded along a continuum – from intuitive, experiential orientations to reflective transposition. At lower levels, science is taught as concrete and emotionally resonant; at intermediate levels, integration varies widely; and at higher levels, teachers engage in epistemological reflection on science teaching and learning.

Enacted PCK

Low CK – Situated, procedural action. Enacted PCK refers to knowledge in use – the decisions made during instruction to sustain or deepen understanding. Among teachers with low CK, enacted PCK manifested as situated knowledge focused on maintaining attention, pace and order. Patricia described her sequence ('starting with a video, asking guided questions, closing with a quiz') as a way to ensure lesson flow and completion of goals. Similarly, Diana evaluated the success of her lesson in terms of task completion, explaining that 'they can identify and recognise each part … maybe we didn't go into depth about each function … but they know how it is composed and where it is located.' Her actions compensated for conceptual limitations through methodological structure and classroom management. At this level, strategies are coherent but function primarily to sustain activity rather than provoke scientific reasoning.

Intermediate CK – Adaptive but uneven performance, characterised by the ability to respond to students' ideas in situ, but with inconsistent depth in the reconstruction of scientific meaning. In the intermediate group, teachers showed a growing capacity to adjust teaching in response to students' ideas, though performance remained highly variable. Javier modified his lesson when he noticed that students associated smoking-related harm solely with the lungs, extending his explanation to the circulatory system: 'I wanted them to realise it's not just the lungs that are affected.' His decision turned a misconception into an opportunity for causal reasoning.

Conversely, Karina responded to students' confusion between 'eating' and 'nutrition' by adjusting her explanation to 'what they were mixing up.' This displayed diagnostic sensitivity but did not achieve structural understanding. These contrasts indicate that conceptual mastery alone does not ensure reflective action: some teachers recontextualise science, whereas others fragment it into descriptive sequences.

High CK – Reflective pedagogical inquiry in action, understood as the capacity to transform emergent classroom situations into opportunities for collective knowledge construction through dialogue and epistemic reflection. Teachers with high CK and PCK demonstrated reflective pedagogical thinking while teaching. Cristian used an unexpected student claim – 'the kids thought a pear could be a lipid' – to stimulate doubt and collective reasoning: 'I tried to prompt them to question themselves, without having a specific answer myself.' Doris used students' drawings of the digestive system to discuss misconceptions, reminding them that 'models can lead to conceptual errors if they aren't analysed and discussed.' In both cases, action became shared inquiry, using uncertainty and dialogue as tools to build scientific understanding.

Overall progression in enacted PCK. Enacted PCK illustrates that effective teaching depends not only on teachers' knowledge but on how they mobilise it in the moment. At lower levels, action organises; at intermediate levels, it adjusts; at higher levels, it interprets and reconstructs. This progression suggests that enacted PCK develops not only in the capacity to act, but in the ability to interpret and transform classroom events through disciplinary and pedagogical reasoning.

Pedagogical reflection and projection

Pedagogical reflection constituted the space in which teacher knowledge was reorganised through experience. A progression was observed – from intuitive awareness to metacognitive review and intentional reconstruction of professional knowledge. At lower levels, reflection appeared as spontaneous responses to contingencies and student relationships; at higher levels, it became an analytical practice grounded in evidence, professional judgement and formative purpose.

Low CK – Intuitive, situational reflection. Among teachers with low CK, reflection emerged as a spontaneous, situational process. Amalia acknowledged that many of her decisions arose 'in the moment,' guided by emotional closeness with her group. Her reflection relied more on empathy than on systematic analysis and functioned as an adaptive mechanism aimed at sustaining engagement. At this level, intuition substitutes for conceptual planning, and reflection serves an immediate regulatory rather than transformative role.

Intermediate CK – Deliberate, improvement-oriented reflection. In the intermediate group, reflection took on a more deliberate, improvement-oriented character. Kathy identified how timing, student responses and comparisons across classes informed her decisions, noting that 'the students' opinions were very interesting, so I preferred to spend more time on them.' Javier projected continuity in learning: 'I think I can wrap it up in the next class when they explain their poster to me,' demonstrating a sequential view of instruction. Marcela described a shift toward meaning-making: 'What has changed is that I now try to find meaning in learning – not for me, but for them.' Together, these teachers displayed a developing reflective PCK in which experience becomes a source of professional knowledge.

High CK – Systematic, epistemological reflection. Among teachers with greater integration of CK and PCK, reflection reached a systematic and epistemological level. Cristian evaluated his lesson with precision – 'The class met about 80% of my expectations' – while acknowledging evidence of learning through students' predictions and embracing uncertainty: he aimed to 'prompt them to question themselves without having a specific answer.' Doris analysed the epistemic function of models, warning that 'if they are not discussed, they can lead to conceptual errors,' interpreting students' representations as windows into their thinking. Both demonstrated metacognitive reflection that turns teaching into an object of inquiry.

Overall, pedagogical reflection evolved from intuitive reaction to systematic interpretation of practice. At lower levels it operated as affective adjustment; at intermediate levels, as self-evaluation and projection; and at higher levels, as epistemological inquiry. This trajectory shows that PCK development entails not only acting with knowledge but also thinking with and about it, integrating experience as a source of understanding and continuous improvement.

To facilitate interpretation of the qualitative findings, Table 3 summarises the characteristic patterns identified across the four dimensions analysed (CK–PCK articulation, personal PCK, enacted PCK, and pedagogical reflection). The synthesis highlights how increasing levels of conceptual knowledge were associated with qualitatively different forms of pedagogical reasoning and practice, while also revealing the heterogeneous

Table 3. Qualitative patterns associated with different levels of conceptual knowledge.

CK Level	CK–PCK Articulation	Personal PCK	Enacted PCK	Pedagogical Reflection
Low CK	**Compensatory functional PCK**. Reliance on concrete resources and sensory representations. Scientific explanations remain superficial and focus on making phenomena tangible.	**Intuitive, relational PCK**. Decisions prioritise motivation, relevance and affective engagement rather than conceptual precision.	**Situated, procedural action**. Teaching focuses on maintaining attention, pace and task completion.	**Intuitive, situational reflection**. Reflection is spontaneous and responsive to immediate classroom contingencies.
Intermediate CK	**Emerging conceptual–pedagogical integration**. Biological concepts are linked to everyday experiences through dialogue, experimentation and causal reasoning.	**Heterogeneous personal PCK**. Coexistence of integrated and descriptive approaches; varying capacity to transform science into meaningful learning.	**Adaptive but uneven performance**. Teachers respond to students' ideas, though depth of conceptual reconstruction remains inconsistent.	**Deliberate, improvement-oriented reflection**. Experience becomes a source of pedagogical adjustment and instructional planning.
High CK	**Transformative and reflective PCK**. Disciplinary knowledge is reconstructed to guide learning and promote inquiry.	**Metareflective personal PCK**. Teaching decisions are critically examined and transformed in light of disciplinary and epistemological considerations.	**Reflective pedagogical inquiry in action**. Classroom events become opportunities for collective knowledge construction and epistemic dialogue.	**Systematic, epistemological reflection**. Teaching is analysed as an object of inquiry and professional knowledge development.

trajectories that emerged once a minimum threshold of disciplinary understanding had been achieved.

Triangulation of results

The integration of quantitative and qualitative findings shows that the relationship between CK and PCK is complex and non-linear. Quantitatively, the low correlation and absence of significant group differences suggest that stronger CK does not automatically translate into more developed PCK. Qualitatively, however, three progressive trajectories were identified in which CK served as the structural basis for PCK, but its expression depended on teachers' reflective capacity and didactic awareness.

This apparent discrepancy is resolved when recognising that PCK is not accumulated but transformed through practice: CK is reorganised through pedagogical action. Teachers with medium or high CK may therefore exhibit markedly different performances depending on the degree of reflective integration of their knowledge. Triangulation confirms that PCK development cannot be explained solely in terms of content, but through the dynamic interaction among knowledge, action and reflection. This underscores the need for teacher education approaches that are mixed-methods, context-sensitive and that recognise PCK as situated professional knowledge.

Discussion

Structural relationship between CK and PCK

This study confirms the complex and non-linear nature of the relationship between Conceptual Knowledge (CK) and Pedagogical Content Knowledge (PCK) among primary teachers. Quantitatively, the low correlation and lack of significant group differences indicate that PCK does not increase proportionally with conceptual mastery. This partial independence aligns with Santibáñez et al. (2025b), where contextual, experiential and reflective factors repeatedly mediated the CK–PCK relationship. PCK thus appears less as an additive extension of CK and more as a transformative form of knowledge reorganised through pedagogical practice.

Qualitative evidence clarifies this structure. Teachers with limited CK rely on concrete strategies and perceptual representations, whereas those with intermediate or higher CK employ scientific understanding to support causal explanations, instructional decisions and reflective analysis. Yet within similar CK bands, PCK varies widely. This suggests functional thresholds rather than linear progressions: once a minimal conceptual base is reached, teachers diverge based on their opportunities to integrate knowledge pedagogically.

These findings echo Hamed et al. (2020), who showed that preservice teachers with comparable CK display different pedagogical performances depending on reflection and modelling experiences. Ahtee and Johnston (2006) likewise noted that disciplinary confidence shapes explanation quality and teachers' willingness to address scientific content. Weak CK often leads to control strategies or oversimplification – patterns observed among low-CK participants here. Conversely, more structural disciplinary understanding supports the transformation of content into meaningful cognitive experiences.

Evidence from Alake-Tuenter et al. (2012) reinforces this point: scientific competence depends not on the quantity of knowledge but on the ability to mobilise CK in inquiry-rich contexts. PCK develops by integrating conceptual and pedagogical knowledge in situated practice – the functional threshold also identified in this study.

Professional interaction further mediates this integration. Nilsson and Van Driel (2010) found that collaborative environments promote deeper CK–PCK articulation by prompting teachers to reinterpret disciplinary ideas through planning, teaching and collective reflection. Here, teachers with stronger PCK displayed such reflective capacities, identifying conceptual errors, interpreting students' representations or reconstructing explanations based on emerging evidence. Lewis (2019) similarly showed that active experiences requiring teachers to think as both learners and mediators strengthen their epistemological understanding of science.

In sum, the CK–PCK relationship in primary education is neither causal nor proportional. CK functions as a necessary but insufficient condition: a certain conceptual threshold enables viable science teaching, but the shift toward reflective PCK depends on epistemological awareness, professional interaction and opportunities for situated reflection. Structurally, PCK emerges as a form of professional thinking that transforms scientific knowledge into pedagogical understanding – activated only when teachers integrate science, teaching and reflection coherently.

Mediating and epistemological processes in PCK development

The findings indicate that PCK develops through mediating processes that transform disciplinary understanding into knowledge for teaching. Unlike the linear relationship between CK and PCK reported by Fukaya et al. (2025), the qualitative evidence here points to a more interpretative and situated dynamic. Both perspectives converge on one point: CK operates as a threshold. Only from a sufficient conceptual base can reflective forms of PCK emerge. The distinction lies in how this transformation occurs – while Fukaya and colleagues describe cumulative progression, this study characterises it as epistemic reconstruction mediated by practice.

This interpretation aligns with Davis (2004), who argues that PCK arises from knowledge integration, whereby prior conceptions are reorganised around explanatory principles and teaching contexts. Such integration appeared among teachers who reinterpreted student misconceptions as windows into their thinking. An epistemological understanding of science – its tentative, explanatory nature – thus becomes the bridge between CK and PCK (Davis, 2004; Hanisch & Eirdosh, 2023).

Studies by Alake-Tuenter et al. (2013) and Lewis (2019) highlight that this integration requires formative experiences in which teachers engage with science as reflective inquiry. Teaching and learning science simultaneously foster metacognitive understanding that connects disciplinary ideas with pedagogical action. In this study, teachers who successfully linked biological phenomena to students' experiences or questions exemplified this inquiry-oriented professional thinking.

Corni et al. (2022) further show that problem-based practices support the reconstruction of prior ideas and the appropriation of scientific epistemologies. Teachers with higher PCK here exhibited comparable processes, moving from descriptive explanations to functional interpretations.

Thus, PCK emerges as a form of professional thought arising from the interplay of knowledge, inquiry and reflection. While quantitative analyses capture its relationship with CK, qualitative evidence shows how PCK consolidates when teachers teach to understand rather than merely to transmit what they know.

Formative implications for PCK development

The findings suggest that strengthening PCK among primary teachers requires opportunities that deliberately integrate conceptual knowledge, reflective practice, and collaborative inquiry. This echoes Appleton's (2006) characterisation of primary science PCK as knowledge constructed 'from practice toward understanding,' through experimentation, adaptation, and the refinement of activities that work. However, such adaptation becomes limited when teachers lack sufficient disciplinary grounding to transform experience into pedagogical insight (Appleton, 2006; Cobo-Huesa et al., 2022).

These findings carry particular implications for primary teacher education. Unlike secondary science teachers, primary teachers are expected to develop pedagogical expertise across multiple disciplines simultaneously, often through fragmented preparation programmes in which disciplinary and pedagogical learning remain separated. Our results provide support for more integrated approaches in which CK and PCK develop in interaction rather than in sequence. Consistent with previous research (Kind & Chan, 2019; Nilsson, 2008), the results suggest that a minimum conceptual threshold may be necessary for reflective forms of PCK to emerge, but that further PCK development depends less on the accumulation of additional content knowledge and more on opportunities to pedagogically reorganise and reinterpret existing understanding.

The study also has implications for in-service teachers working under conditions of limited time, curriculum pressure, and accountability demands. Under such conditions, professional development initiatives centred exclusively on new methodologies, technologies, or disciplinary updating may have limited impact on science PCK if they are not accompanied by opportunities for pedagogical reasoning about content. Rather than adding new demands, PCK-oriented professional learning should be embedded within teachers' existing instructional work.

A feasible approach, consistent with both the present findings and previous research on effective professional development (Desimone, 2009; Luft et al., 2022; Yang et al., 2020), would involve short collaborative cycles in which teachers identify key scientific ideas, anticipate students' likely interpretations and misconceptions, analyse representations and explanatory models, implement instructional decisions, and subsequently examine evidence of student thinking to refine future teaching. Importantly, such processes may help teachers recognise not only what they know, but what additional disciplinary understanding is required to support learning in particular topics.

Viewed from this perspective, PCK development does not depend on becoming a disciplinary specialist before teaching science effectively. Rather, it depends on learning to think pedagogically with science: using conceptual knowledge as a resource for interpreting classroom events, making instructional decisions, and transforming teaching experience into professional understanding.

Integrative synthesis

The findings confirm that the relationship between Conceptual Knowledge (CK) and Pedagogical Content Knowledge (PCK) in primary teachers is neither linear nor cumulative, but a transformative process shaped by reflection, experience, and pedagogical mediation. CK operates as a threshold condition: when insufficient, it constrains the emergence of PCK; once a functional level is achieved, further development appears to depend less on the accumulation of additional content knowledge and more on opportunities to reinterpret and mobilise existing knowledge pedagogically. Between these poles lies a range of intermediate trajectories in which PCK depends less on the quantity of knowledge possessed than on how it is transformed for teaching.

This interpretation provides empirical support for a phenomenon recognised in recent research frameworks – such as those synthesised by van Driel et al. (2023) – but rarely documented in practice: the transition between personal and enacted PCK. Although the Refined Consensus Model distinguishes these dimensions theoretically, few studies have analysed them simultaneously and within classroom contexts, particularly in primary education. The present study contributes to this gap by combining declarative and observational measures that capture how teacher knowledge is transformed during instruction.

The findings also carry implications for the distinctive conditions of primary teacher education. Unlike secondary teachers, primary teachers are expected to develop pedagogical expertise across multiple disciplinary domains simultaneously, often under fragmented preparation structures. The present results suggest that effective preparation may depend less on separating CK and PCK development and more on creating opportunities for their continuous integration through practice, reflection, and analysis of student thinking.

A limitation of this study is that teaching experience was not systematically analysed as a variable. Although variation in experience was observed among participants, the study design focused on the relationship between conceptual knowledge and enacted PCK in specific teaching contexts. Future research could examine how teaching experience interacts with the development and enactment of PCK.

Taken together, these contributions outline an empirical model of PCK progression in primary teachers, evolving from functional and experiential forms of knowledge toward reflective and epistemic understanding. Rather than proposing a linear pathway, the study identifies conditions that appear to support this progression, including opportunities for pedagogical reflection, collaborative inquiry, and the reinterpretation of disciplinary knowledge through practice. Understanding this dynamic is crucial for designing initial and continuing teacher education programmes that strengthen science teaching from its professional core: thinking pedagogically with and about science.

Ethics statement

All participants provided informed consent prior to data collection. Participation posed no risk, and permissions for classroom video recordings were obtained from the school leadership. At the time of data collection, no institutional ethics committee process was required for studies of this nature.

Disclosure statement

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

Use of generative artificial intelligence

ChatGPT (OpenAI, GPT-4, 2024) was used in a limited manner to assist with English language editing, word-count reduction, and preliminary organisation of qualitative categories. All analyses and interpretations were conducted and validated by the authors.

Data availability statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request. To protect participant confidentiality, raw video data cannot be shared.

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