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Systematic Review

Modelling STEM Teachers' Pedagogical Content Knowledge in the Framework of the Refined Consensus Model: A Systematic Literature Review

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Abstract: Science education researchers have developed a refined understanding of the structure of science teachers' pedagogical content knowledge (PCK), but how to develop applicable and situation-adequate PCK remains largely unclear. A potential problem lies in the diverse conceptualisations of the PCK used in PCK research. This study sought to systematize existing science education research on PCK through the lens of the recently proposed refined consensus model (RCM) of PCK. In this review, the studies' approaches to investigating PCK and selected findings were characterised and synthesised as an overview comparing research before and after the publication of the RCM. We found that the studies largely employed a qualitative case-study methodology that included specific PCK models and tools. However, in recent years, the studies focused increasingly on quantitative aspects. Furthermore, results of the reviewed studies can mostly be integrated into the RCM. We argue that the RCM can function as a meaningful theoretical lens for conceptualizing links between teaching practice and PCK development by proposing pedagogical reasoning as a mechanism and/or explanation for PCK development in the context of teaching practice.

Keywords: pedagogical content knowledge (PCK); refined consensus model (RCM); pedagogical reasoning; teaching practice; science teaching; literature review



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While classroom learning can be affected by a variety of factors, Hattie [1] argues the educational research community should focus on the greatest source of variance that can make a difference to learning in class—the teacher—if findings are to inform more effective learning. Within the broad context of science education, researchers recognise the importance of teachers in supporting student learning, with many turning their attention to the pivotal role of school teachers' professional knowledge for quality teaching [2–4]. To characterise quality teaching, researchers conceptualised the necessary professional knowledge as teachers' pedagogical content knowledge (PCK). More recent research supports the claim that PCK underpins effective teaching [5,6]. However, some researchers point out that while previous studies confirm positive links between PCK and effective teaching, they do not uncover developmental mechanisms related to PCK [7,8].

A widely recognized impact factor for PCK development is practical teaching experiences. Korthagen and colleagues argued 1999 that the development of applicable PCK in science fields and beyond could be facilitated through practical teaching experiences [9], and ten years later Grossman et al. argued that actual classroom teaching can give teachers the opportunity to experiment with and explore their understanding of teaching and learning processes [10]. In 2015, after more models emerged that could facilitate the exploration of links between science teachers' PCK and their practical classroom experiences, there was a growing desire among researchers for a consensus. In 2019, earlier discussions were channelled into the refined consensus model (RCM) (a list of all abbreviations in this

paper can be found in Appendix A) of PCK in science education [11]. In the RCM of PCK, researchers conceptualise practical teaching experiences (in the cycle of planning, teaching and reflecting in/on teaching situations) as core to teachers' PCK. By recognising practical teaching activities as opportunities for this unique form of teacher professional knowledge to be both manifested and generated, as teachers engage in pedagogical reasoning during the teaching cycle, the RCM stresses the context-specific, situated nature of PCK. Even though practical teaching experiences are established to be important for PCK development, the variety of influencing factors and interrelations among constructs, especially since the RCM was established, are less well outlined and textured.

In this paper, it is our intention to explore the breadth of studies in the realm of science education that investigate relationships between PCK (development) and teaching practice with and without explicit mention of the RCM. We will therefore use the RCM of PCK as a conceptual framework for our methodology and the conceptualisation of our results. As this study will test the explanatory power of several PCK studies and the outlined relationships and processes in the context of the RCM, we also evaluate, in the guise of our data, the explanatory capabilities of the RCM for PCK research in science education.

1. Modelling PCK

PCK emerged as a particularly important construct for science teachers because it has the potential to characterise expert teachers' professional knowledge and skills and predict effective teaching [5,6,12]. As a result, PCK has become a central component of many university-based science teacher education programs [8], in which instruction featuring the nature of students' preconceptions and conceptual difficulties, instructional strategies (including the use of analogies and metaphors), assessment, and curriculum were promoted as affording pre-service science teachers opportunities to begin building relevant PCK for their profession [13].

However, modelling PCK in teacher education has proven difficult and has a diverse history [14]. Initially, Shulman [15,16] viewed PCK as an amalgam of content and pedagogy, so PCK could be seen as a new and distinct form of knowledge transformed from content knowledge (CK) that has to do with subject matter, representations, and phenomena, and pedagogical knowledge (PK), which is general knowledge about learning and teaching, as well as a kind of overlap of CK and PK. Numerous conceptual frameworks for PCK (e.g., Grossman, 1990 [17]; Magnusson et al. (1999) [4]; Park & Oliver, 2008 [18]) were developed. These models can also be differentiated as rather integrative or transformative models of PCK [19,20]. This differentiation captures whether PCK was considered more of a unique entity (transformative model) or not (integrative model) and was carried out because transformative PCK models are considered more appropriate for explaining developmental processes regarding PCK [19]. Unfortunately, rather than clarifying research directions, it is possible that these different schools of thought about the nature (and development) of PCK in science education began hampering progress in the field and in time led to calls for consensus around the conceptualisation of PCK [21].

Based on the different models, different knowledge bases constitute PCK. More pronounced knowledge bases can result in more pronounced PCK. Nevertheless, there is a consensus in the PCK research community that a teacher's PCK level depends more on the degree of integration and coherence among the components [22] than on these knowledge bases themselves. It is also consensus that PCK is both knowledge and skills, that it is topic specific, and that it is highly personal and idiosyncratic [23]. Consequently, science teachers' PCK per se can only be described as for individual teachers. From this perspective, research on the nature and development of science teachers' PCK needs to pay more attention to the interactions between PCK components or to other variables (e.g., attitudes and beliefs) than to the separate components [22] to obtain evidence for influencing factors of a generic nature.

In 2016, based on the earlier work of Gess-Newsome and colleagues [14], Carlson et al. repositioned PCK in teachers' professional knowledge for teaching science, as depicted

in the RCM of PCK for teaching science [11]. Building on the existing PCK components of earlier models, the RCM introduces three differentiated realms of PCK that inform the understanding of potential sources and/or mechanisms for the development of science teachers' PCK. These realms include collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). According to the RCM, cPCK exists within the larger science education communities that researchers and teachers belong to [11]. Pre-service, as well as in-service, teachers become aware of cPCK through their immersion in the wider science education community during university-based teacher education and beyond, where they are exposed to and experience the use of various curricular and teaching documents and resources and engage in interactions with other teaching professionals. They begin developing, amongst other forms of knowledge, a unique and personal form of PCK termed pPCK that over time is increasingly informed by the teachers' experiences of classroom teaching. Then, pPCK becomes a major intellectual resource that enables science teachers to think and perform as teachers both explicitly and tacitly [24,25].

In its centre, the RCM explains that during the act of teaching, an individual teacher uses a process of pedagogical reasoning (decision-making) to manifest aspects of his/her pPCK as ePCK during the plan-teach-reflect (teaching) cycle [24]. Therefore, teaching practice becomes a forum for knowledge exchange and PCK development, and pedagogical reasoning is the mechanism by which this exchange and development occur. Double-headed arrows in between the realms of ePCK and pPCK in the RCM indicate that teaching practice can in turn inform further pPCK development, i.e., knowledge exchanges across the two realms can lead to changes in both pPCK and ePCK.

Delving into the central ePCK realm of the RCM, Alonzo and colleagues identify two distinct plan-teach-reflect cycles: a macro cycle focused on whole lesson planning, teaching, and retrospective reflection and a micro cycle within the teach phase of the macro cycle that features in-the-moment teaching decisions made during classroom instruction [24]. In the micro cycle, ePCK guides the interpretation (noticing and reflecting) of teaching situations that arise during the lesson and the planning decisions made and actions taken in response to those moments. Using these cycles, researchers argue that ePCK is related to a teacher's planning (ePCKp), teaching (ePCKt), and reflecting (ePCKr).

The ability of planning for teaching a specific topic for a specific learning group and teachers' knowledge and skills for enhanced student outcomes were defined as PCK by Gess-Newsome (2015) [14]. The topic specificity (as well as all further pedagogical reasoning related to the specific students in the specific situations) of lesson planning is clearly addressed as well. The act of teaching is more deeply dependent on the teacher since planning knowledge can be learned, but the teacher's perception of a teaching situation and thus his or her actions are significantly influenced by his or her classroom experience [26]. However, what is important for the professional development of science teachers is not only their teaching experience and the knowledge gained from it but the reflection behind the act of teaching when interacting with the students (reflection in action), as well as the reflection on the teaching, the planning, and the students' outcomes (reflection on action) [27]. Both scales for reflective thinking are represented within the teaching cycles on the micro-retrospective macro level.

Furthermore, the RCM anticipates that ePCK is linked to pPCK in complex ways and that testable inferences can be drawn about these links. Practical teaching experiences (e.g., during university-based teacher education programs) are important means of individual PCK development [10,24] since teaching practice requires pedagogical reasoning to enact PCK and reflect upon those experiences [28,29]. Thus, these interactions between pPCK and ePCK constitute a link between a teacher's teaching experiences and his/her PCK development that is accessible to research. However, there are presently hardly any conclusive overviews on the actual developmental mechanisms between PCK and teaching practice that have been studied in the science education literature [8,30].

In their review of how science teachers' PCK was investigated in empirical studies, Chan and Hume confirmed that researchers conceptualise and operationalise PCK dif-

ferently as they identify diversity in the research they reviewed in aspects such as focus, sample, and method of data collection and/or data analysis [23]. They concluded that the standardising of a conceptual framework was needed to investigate and discuss interrelationships between PCK and teaching practice and to bring greater coherence to research in the field. This study will systematically explore interrelations between PCK and practical teaching experiences with respect to Chan and Hume [23] four research foci: (1) the nature of science teachers' PCK, (2) the development of science teachers' PCK, (3) the changes in science teachers' PCK during professional development or the use of an intervention, and (4) the relationships between PCK and other variables. To evaluate the potential influences of the recently developed RCM, the reviewed studies will be differentiated into studies prior to the introduction of the RCM and studies published later. The purpose is to outline to what extent the RCM is actually used by researchers in the field and to better assess how the RCM integrates prior PCK conceptualisations.

Research Questions

Based on the findings by Chan and Hume [23], this study explores in greater depth the nature of (applicable) PCK, including its conceptualisations and how it potentially develops. To better differentiate studies with respect to their PCK conceptualisations, the sample of studies to be reviewed was divided by year of publication. The year in which the first study refers to the RCM is chosen as the cut-off date for the division of the sample. For this review, all studies published up to 2019 are therefore defined as studies before the RCM and all studies published since 2020 as studies after the RCM. In a set of two research questions, this study summarises aspects of the reviewed studies to evaluate the representativeness of the review and to give an overview of the dissemination of PCK models. Furthermore, we examine how the samples of the studies before and after the RCM relate to each other:

- RQ 1: What is the sample of the studies examined (in terms of sample, design, and methodology) and how do the studies before the RCM differ from the studies after the RCM in these aspects?
- RQ 2: How is PCK conceptualised in the reviewed studies and how did the use of models change with the publication of the RCM?

In a set of two further research questions, this review identifies features of the interplay between science teachers' PCK and their practical teaching experiences. RQ 3 focusses on a special feature of the RCM (the plan-teach-reflect cycle) that is particularly relevant to analysing teaching practice. In RQ 4, teaching practice is considered more broadly than just planning, teaching, and reflecting. Rather, we use the term 'practice' to encompass more influencing aspects of professional development for teachers such as teacher training programs, personal values and beliefs (which can develop during teachers' practice), or peer observations or collaborative teaching.

- RQ 3: To what extent can the reviewed studies be classified in the macro respectively micro reasoning cycle?
- RQ 4: What effects are discussed in the context of PCK, PCK components and aspects of teachers practice in the research?

2. Method

To search the field of science teacher education for studies related to PCK and teaching practice, a systematic literature review following the approach taken by Bennett et al. [31] was conducted. First, keyword searches in research databases (e.g., ERIC, PsychINFO, Web of Science) were conducted according to the goals of this study, using the search terms 'PCK', 'teaching practice', 'pedagogical reasoning', 'STEM', and the STEM subjects to retrieve an exhaustive list of potentially relevant studies. The identification of suitable articles included peer-reviewed research articles for science teachers' PCK from 1986, when

PCK was first conceptualised, to the end of 2021. Based on the quality criteria (see Table 1), all studies were screened by reading the titles and abstracts.

Table 1. The criteria for inclusion or exclusion of studies.

Inclusion Criteria		Description of Excluded Studies
1	Peer-reviewed	Not peer-reviewed articles
2	English or German language	Other languages
3	Empirical studies	Nonempirical in nature (e.g., discussion paper)
4	PCK or pedagogical reasoning of science and/or mathematics teachers	Mathematics knowledge for teaching (MKT) STEM * teachers' TPACK /TPCK ** Teacher educators' PCK Early childhood teachers' PCK Teacher assistants' and instructors' PCK Students' reasoning
5	Investigating science teachers' PCK in practical or simulated teaching situation	Paper-pencil tests (Method) Course or professional development without a practical situation

* STEM: Science, Technology, Engineering, & Mathematics. ** Technological Pedagogical Content Knowledge was disregarded because of its assumed irrelevance for links between pPCK and ePCK. In this Review TPACK/TPCK is seen as an aspect of external conditions.

To analyse the RQs in relation to the theoretical framework of the RCM, all studies were processed according to the following procedure: (1) Identifying relevant segments in the abstract and full text of the papers. (2) Inductive or deductive coding by a first rater who was well acquainted with the RCM (first author). The first rater developed a coding manual (i.e., categories and definitions for the categories). (3) Recoding subsets of the studies by an independent second rater (third author), which was done on the basis of the developed coding manual. (4) Calculating interrater agreement corrected for chance (Cohen's κ). A summarising overview of the systematic literature review is shown in Figure 1.

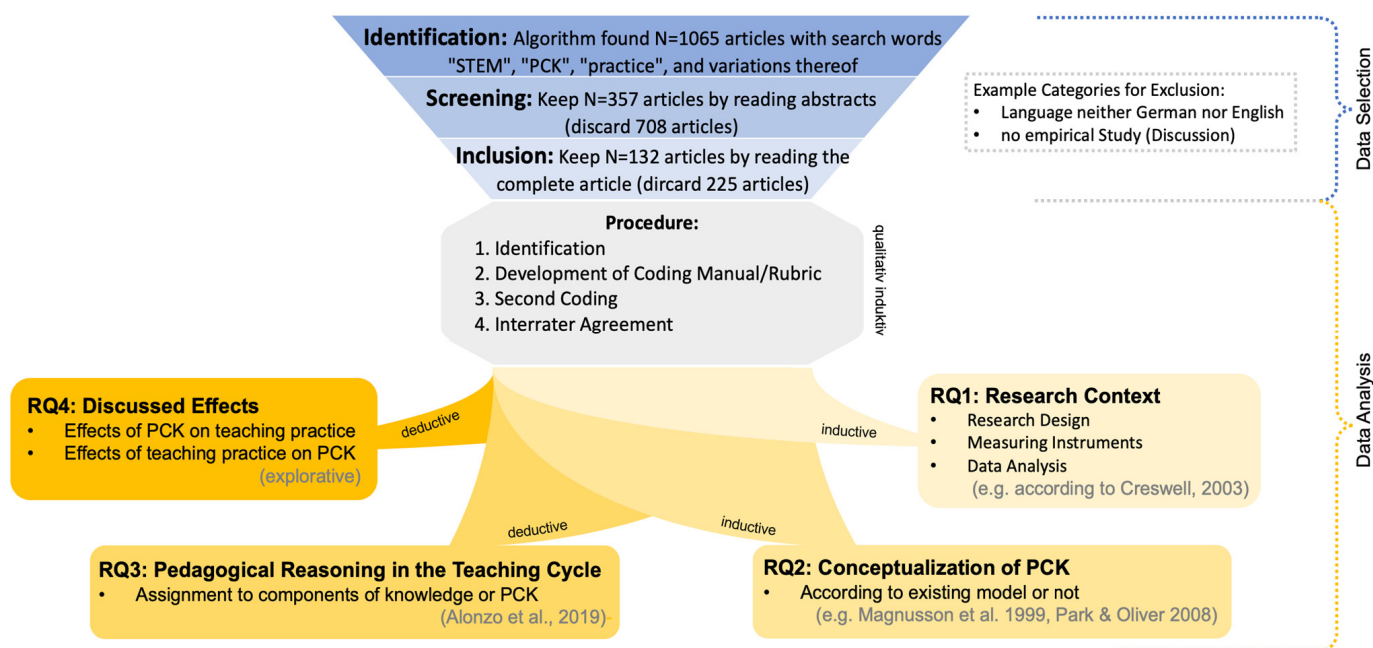


Figure 1. A schematic visualization of the literature review method.

For RQ1, the research methods for data collection as well as the methodological approach and the study background were coded to help evaluate the empirical robustness of findings related to teaching practice and development of applicable PCK that Wilson et al. had observed were unclear in the literature as a result of mainly small sample sizes [32]. The research methods were inductively coded, and the methodological approaches were differentiated as qualitative, quantitative, or mixed-methods study designs [33]. This research question provides evidence for the representativeness of the review with regards to the sampled studies in reference to other reviews [23].

For RQ2, conceptualisations of PCK and teaching practice were analysed to detect preferred PCK models. Inductive-deductive content analysis was utilized to identify PCK models, where established models (e.g., Magnusson et al. (1999) [4]; Park & Oliver, 2008 [13,18]; and others) formed the initial coding units and unanticipated PCK models were added as categories in the coding process. In addition, at this point, the discourse of the transformative or integrative view on PCK was related to the PCK models themselves as well as to the research foci proposed by Chan and Hume [23].

In RQ3, references in the studies to pedagogical reasoning in the teaching cycle were examined in order to identify instances where pedagogical reasoning was used as a means of mediating PCK development by helping teachers to unpack their PCK and articulate their knowledge [28]. A deductive coding approach was applied using the concepts of ePCKp, ePCKt, and ePCKr from the RCM in micro or macro teaching cycles as defined by Alonzo et al. [24]. In this way, it can be checked whether the studies fit into the reasoning cycles.

For RQ4, the effects of the interactions between aspects of PCK were explored in order to determine what relationships were established in the studies. The relationships included interactions between PCK components and aspects of teaching practice that were identified as influences in the studies. This RQ attempts to provide a possible perspective for further research, e.g., where missing links are identified.

3. Results

3.1. Research Context (RQ 1)

As an important indicator for the sample, we first considered the expertise level of the participants in the reviewed studies. Pre-service teachers, e.g., [34], novice teachers e.g., [35], and teachers with more than five years of teaching experience e.g., [13] participated in the selected studies. The majority of the studies used experienced teachers to study PCK in relation to teaching practice ($N = 65$), followed by pre-service teachers ($N = 44$). Some studies used different types of teachers ($N = 7$) in contrast group designs, such as Friedrichsen and colleagues, who compared the knowledge of novice teachers with that of pre-service teachers entering a certification programme [36], and Krepf et al. compared the knowledge of novice and experienced teachers as they assessed teaching and learning in a videotaped lesson [37]. Tal and colleagues considered career-changing chemistry teachers [38]. The grade levels of the investigated teachers in the current review spans a range of $N = 37$ studies with elementary teachers to $N = 15$ studies of teachers teaching secondary 2. Mixed samples (e.g., $N = 29$ secondary 1 & 2 or $N = 10$ secondary 1 & elementary) are also represented. Most studies involved chemistry teachers ($N = 40$), followed by science ($N = 34$), biology ($N = 26$), mathematics ($N = 21$), physics ($N = 19$), elementary science ($N = 6$), and earth science ($N = 4$) teachers. Space science and technology ($N = 2$ each) as well as engineering, science and technology, and STEM research and design were the least studied subject domain in the studies ($N = 1$ each). A difference between the samples of studies before and after the RCM could not be identified under these aspects.

Sample sizes of $N = 1$ e.g., [39] to $N = 210$ were present in the reviewed studies [40]. Only 3.8% of the studies had a sample size of more than 100 teachers, while 67.4% had fewer than 10 participants. Figure 2 illustrates the changes in the sample sizes throughout the years of the studies. Ignoring the used PCK modelling, it is obvious that since the publication of the RCM in the last two years, the studies have investigated the PCK of

more participants. Figure 2 presents the sample sizes of the studies by year of publication. An increase in sample size from 2020 onwards can be seen that was primarily achieved through surveys of pre-service teachers at the researchers' universities e.g., [41,42].

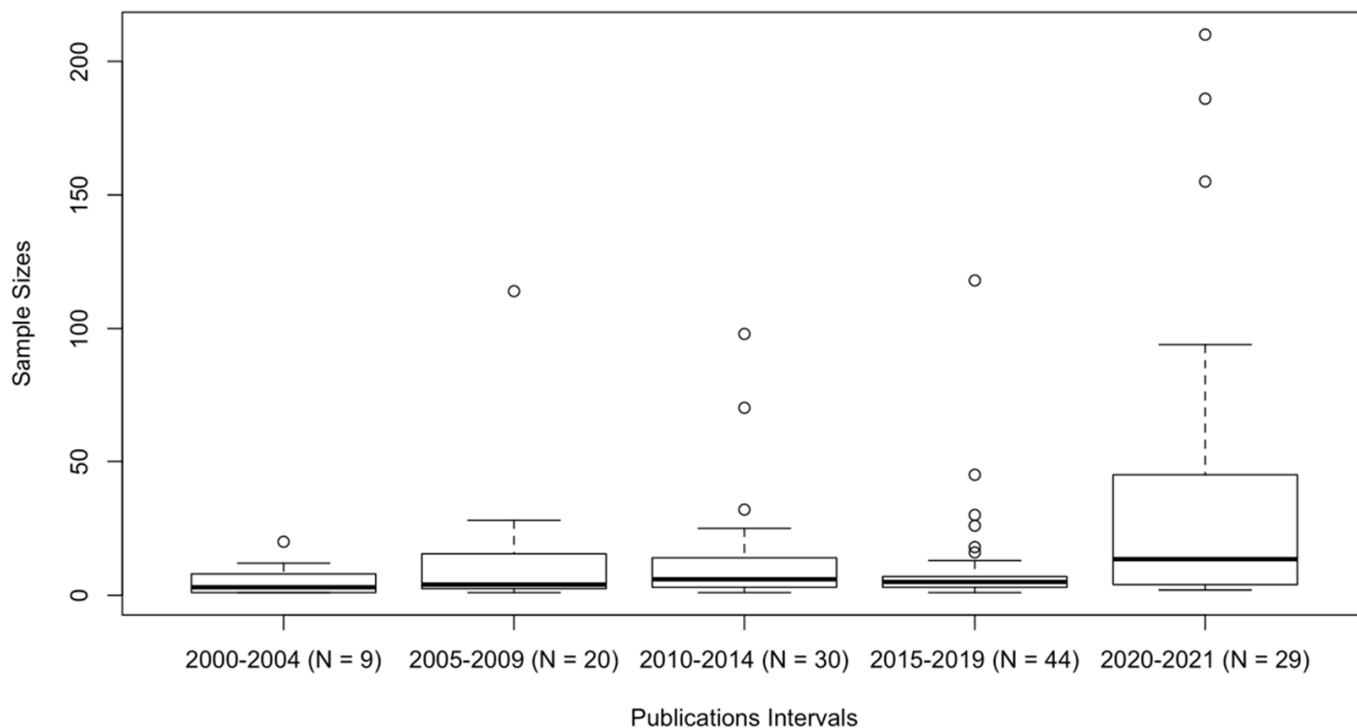


Figure 2. The sample sizes of the reviewed studies according to publication years.

The overview reveals that the majority of studies, i.e., 72.7% ($N = 96$), involved qualitative research approaches, while the remaining 14.4% of studies employed quantitative methods ($N = 8$, thereof $N_{2020-2021} = 5$) and mixed-method designs ($N = 28$, thereof $N_{2020-2021} = 12$). This review identifies ten categories of methods, the frequency of which varies according to the design of more qualitative or more quantitative methods: (1) tests such as pre- and post-tests or questionnaire/surveys with foci on teachers' background variables, teachers' views on student learning, or teachers' CK or PCK ($N = 66$); (2) classroom artefacts, i.e., homework tasks ($N = 21$); (3) interviews ($N = 134$); (4) lesson plans ($N = 101$) in preparation for a lesson, content representations (CoRes) or team planning meetings before classroom implementation in a course or PD program; (5) classroom observations ($N = 134$) based on field notes or videography and often followed by interviews; (6) reflections ($N = 66$) in written or recorded form after classroom teaching as self-reflections or collegial feedback (assessments and assignments) and (7) others ($N = 20$), such as recorded course meetings or concept maps. Overall, it is noticeable that later studies used more quantitative designs. This corresponds with the increase in sample size, probably because quantitative methods in the frequentist paradigm require large sample sizes.

3.2. Conceptualisation of PCK (RQ2)

In line with a previous study by Chan and Hume [23], the analysed studies until 2019, when the RCM was published, were divided into two groups, one comprising studies that conceptualised PCK using integrative PCK models and the other comprising transformative models of PCK (Tables 2 and 3). The first group ($N_{2000-2019} = 11$; 10.8%) considered PCK to be an integration of different knowledge categories rather than its own knowledge category, whereas the second group ($N_{2000-2019} = 91$; 89.2%) conceptualised PCK as an independent knowledge category and thus adopted the transformative model. Except for Bauml [43], all studies in the first group examined the science teachers' PCK in combination

with other knowledge categories such as content knowledge (CK), pedagogical knowledge (PK), contextual knowledge (CxK), knowledge of students (KS) and curriculum knowledge (CuK). Avargil and colleagues was the only study in this analysis to investigate assessment knowledge (AK) by examining the abilities of chemistry teachers to design new assignments to evaluate their students' learning outcomes [44].

Table 2. More integrative PCK models in studies up to 2019.

Integrative							
Model	(N = 11)	CK	PK	CxK	KS	CuK	AK
Cochran et al. (1993) [45]	(N = 1)	1	1	1	1		
Grossman (1990) [17]	(N = 1)	1	1	1		1	
Shulman (1986) [15]	(N = 4)	4	4			1	
Not specified	(N = 5)	4	4	3	1	1	1
<i>Sum of References</i>		10	10	5	2	3	1

Table 3. More transformative PCK models in studies up to 2019.

Transformative								
Model	(N = 91)	KSU	KISR	KA	KC	OTS	Others	Not Specialized
Abell (2008) [21]	(N = 1)	1	1	1	1	1		
Gess-Newsome (2015) [14]	(N = 5)	3	5	1	3	2		
Grossman (1990) [17]	(N = 2)	2	2		1	1		
Hanuscin et al. (2011) [46]	(N = 3)	3	3	3	3	3		
Magnusson et al. (1999) [4]	(N = 31)	28	26	22	23	18		
Park & Oliver (2008) [13,18]	(N = 4)	4	4	4	4	4		
Rollnick et al. (2008) [47]	(N = 2)		1	1	2			
Saxton et al. (2014) [48]	(N = 1)	1	1	1	1	1		
Shulman (1986) [15]	(N = 8)	7	6			1		
Turner-Bisset (1999) [49]	(N = 1)	1	1		1	1	1	
Not specified	(N = 33)	27	27	7	13	8	2	1
<i>Sum of References</i>		78	77	40	52	40	3	1

Almost a third ($N_{2000-2019} = 31$) of the second group who viewed PCK more as a transformed knowledge form used the Magnusson et al. (1999) PCK model and its five unique components as a conceptual framework to guide their studies. These components are: orientations towards science teaching (OTS), knowledge about science curricula (KC), knowledge about student understanding of specific science topics (KSU), knowledge about assessment in science (KA) and knowledge about instructional strategies and representations for teaching science (KISR). Half of these studies ($N_{2000-2019} = 15$) examined all five PCK components e.g., [50]. Another third of the abovementioned studies ($N_{2000-2019} = 32$) did not explicitly rely on any PCK model but referred to some PCK components (especially visible in Table 3). Across the whole of the second group, the most frequently examined components were KSU ($N_{2000-2019} = 78$) and KISR ($N_{2000-2019} = 77$).

Following previous study by Hume et al. (2019), both transformative and integrative views of the nature of PCK have found recognition in the research community. Consequently, the RCM takes the transformative and integrative characteristics of PCK into account. The transformative aspects of the nature of PCK are included in the RCM in the knowledge base shown in the outer circle. During the act of teaching, all knowledge bases are integrated [20] in teachers' ePCK. Therefore, a closer look at the $N_{2020-2021} = 29$ studies published in 2020 and 2021 might be interesting. About a third of the younger studies used elaborate PCK models or no specific respective singular models. It is noticeable that the RCM was used for conceptualisation of every third study shortly after its publication (see Table 4).

Table 4. Used PCK models since 2020.

More Established Models		Refined Consensus Model	Not Specified or Other Models	
Grossman (1990) [17]	(N = 1)	RCM (N = 10) [11]	Abell (2008) [21]	(N = 1)
Magnusson et al. (1999) [4]	(N = 4)		Not specified	(N = 7)
Mavhunga & Rollnick (2013) [51]	(N = 3)			
Park & Oliver (2008) [13,18]	(N = 1)			
Shulman (1986) [15]	(N = 2)			
$N_{2020-2021} = 11$ (37.9%)		$N_{2020-2021} = 10$ (34.5%)	$N_{2020-2021} = 8$ (27.6%)	

As the models used in the reviewed studies should not be considered in isolation from its research aims, Table 5 gives an overview about the used models in relation to the four research foci according to Chan and Hume [23]. Considering all $N = 132$ studies, the RCM is the third most frequent PCK model ($N = 10$). Only the model of Magnusson et al. (1999) and the model of Shulman (1986) are used more often. The most frequent studies referencing to no specific model. The PCK model of Park and Oliver (2008) seemed to best detect the nature of science teachers' PCK (4 of 5 studies), but science teachers' PCK development might be useful with conceptualisations of Grossmann (1990). To focus on changes in science teachers' PCK during professional development or workshops/interventions, researchers used the modelling of Hanuscin et al. (2011). To focus on the relationships between PCK and other variables the conceptualisation of Gess-Newsome (2015) was used in 3 of 5 studies. Assuming that a model should be able to address all four foci, few models stand out: The most often used model from Magnusson et al. (1999) indicates the distribution of the research foci across all studies, and the original model from Shulman (1986) was less used for PCK development research. The RCM is convincing in its equality of distribution across the three research foci of nature, development and change. It can be used less often only for the study of relationships so far, but because there are the fewest studies with this focus, this restriction is comprehensible.

Table 5. Usefulness of PCK Models for researching Nature, Development, Changes, or Relationship of Science Teachers PCK.

Models	Nature	Development	Changes	Relationship	N =
Abell (2008) [21]	0.5	0	0.5	0	2
Cochran et al. (1993) [45]	0	1	0	0	1
Gess-Newsome (2015) [14]	0.2	0	0.2	0.6	5
Grossmann (1990) [17]	0.5	0.5	0	0	4
Hanuscin et al. (2011) [46]	0.333	0	0.667	0	3
Magnusson et al. (1999) [4]	0.194	0.25	0.361	0.194	36
Mavhunga & Rollnick (2013) [51]	0.5	0.25	0.25	0	4
Park & Oliver (2008) [13,18]	0.8	0.2	0	0	5
RCM (2019) [11]	0.3	0.3	0.3	0.1	10
Rollnick et al. (2008) [47]	0	0	0	1	1
Saxton et al. (2014) [48]	1	0	0	0	1
Shulman (1986) [15]	0.286	0.071	0.429	0.214	14
Turner-Bisset (1999) [49]	0	1	0	0	1
not specified	0.378	0.178	0.267	0.178	45
$\emptyset =$	0.374	0.3	0.187	0.143	

In summary, the models of Magnusson et al. (1999) and Shulman (1986) are widely used as a result of their long tradition, but for research foci on the nature, development or change of the RCM and for the relationships of the PCK components, the model of Gess-Newsome (2015) seems to be beneficial.

3.3. Integrability of Reviewed Studies into Concept of Teachers' Pedagogical Reasoning in the Teaching Cycle (RQ3)

In order to summarise interactions regarding pedagogical reasoning, we noted that no study in this review explicitly examines teachers' pedagogical reasoning explicitly. The studies which discussed reasoning refer exclusively to students' reasoning rather than

teachers' reasoning related to decision-making through planning, teaching or reflecting lessons. Therefore, these studies were already excluded from this literature review for the purposes of data collection.

In order to investigate links in the literature between PCK development and practical teaching experiences in greater depth, we used the RCM conceptualisation of the teaching cycle (comprising the macro and micro cycles) as an analytical framework for interpreting how the reviewed studies investigated ePCK (as the part of a unique teacher's pPCK that arises in a unique teaching situation). This approach allowed us to account for most of the concepts in the plan-teach-reflect cycle that were investigated in the reviewed studies and for how these concepts were investigated in relation to the macro and/or micro cycles. A total of $N = 29$ studies investigated the whole teaching cycle, although the researchers examined the cycle in different ways. In order to explore in what ways researchers attempted to capture the teaching cycle elements in conjunction with methods, we cross-tabulated the teaching cycle parts with the methods used (from RQ1) (see Table 6).

Table 6. Research methods used to investigate parts of the teaching cycle in classrooms.

Methods	Plan		Teach		Reflect	
	ePCKp macro	ePCKp micro	ePCKt macro	ePCKt micro	ePCKr macro	ePCKr micro
lesson plans (e.g., CoRes)	49	0	1	1	3	0
classroom observations	13	0	58	4	5	0
classroom artefacts	1	0	3	0	1	0
written reflections	4	0	1	3	31	0
test/assessments questionnaire/ survey	4	1	2	0	2	1
semi-structured interview	33	1	5	2	37	0
stimulated recall interview	0	7	0	21	13	7
unspecified interviews	4	0	3	0	1	2
others	1	0	1	0	1	0
Σ *	109	9	74	31	94	10

* Note that $N = 11$ studies use more quantitative methods, $N = 93$ studies use qualitative methods and $N = 28$ studies use mixed methods to assess one part of a teaching cycle.

As already identified in RQ1, the majority of the studies use qualitative methods. With the exception of lesson plans ($N = 49$) and written reflections ($N = 31$), which capture important dimensions of the teachers' pedagogical reasoning, the studies use methods that attempt to capture the teaching cycle on a macro level (semi-structured interview: $N = 81$; classroom observation: $N = 80$). Planning, teaching and reflecting on a micro level were mostly analysed using simulated recall interviews. Micro ePCKt was examined additionally with classroom observations or written reflections. At least $N = 23$ of the $N = 94$ (24.5%) of the studies on macro ePCKr were concerned with drawing conclusions about the micro ePCKt.

In summary, all studies seem to address at least one aspect of the teaching cycles. It is evident that the methods used are intended for the combined investigation of certain steps of the cycle. Presumably, it is also not useful to research only specific aspects of classroom practice. Appropriate conceptual tools to capture teachers' pedagogical reasoning during the teaching cycles seem to be content representations (CoRes) for macro and professional-experience repertoires (PaP-eRs) [52,53] during classroom observations, interviews for macro ePCKt and interviews or written reflection during (guided) macro ePCKr.

Teachers' micro ePCK was generally analysed less often. Whether micro reasoning is of less importance to researchers or it is more difficult to analyse cannot be said at this point. For the research on micro ePCK, the stimulated recall interview seems to be a common instrument. Nevertheless, a lack of research seems to be recognisable here.

3.4. Interplay of PCK Components and Practice (RQ4)

In order to refine our understanding of possible (empirically established) relationships between PCK and teaching practice, identified segments in the studies were coded. Assuming that each component can influence all other components, the first step was to analyse which relationships were mentioned in the studies. With substantial interrater reliability (see Table 7), $N = 149$ mentioned relationships could be identified.

In order to show more clearly how the effects discussed by the researchers consider the RCM (i.e., collective, personal and enacted PCK as well as pedagogical reasoning), Figure 3 displays the effects between PCK and teaching practice, which were discussed in at least two studies. All concepts (terms) in the research context of PCK and teaching practice were categorised into four groups for clarity: (1) PCK components, not specified whether integrative or transformative; (2) PCK realms within the RCM; (3) pedagogical reasoning as it relates to the teaching cycle and (4) other concepts discussed in studies that are not specifically related to PCK. If cause-and-effect relationships or cause-and-effect statements (e.g., ‘this study indicate[s] that a professional learning community in [. . .] can be a powerful method to enhance personal PCK and collective knowledge’; [54], p. 295) were discussed in the studies, then these relationships were illustrated in Figure 3 using arrows. It should be noted that these implications are not necessarily direct research findings but conclusions interpreted by the researchers in the abstract or discussion section (see the method section).

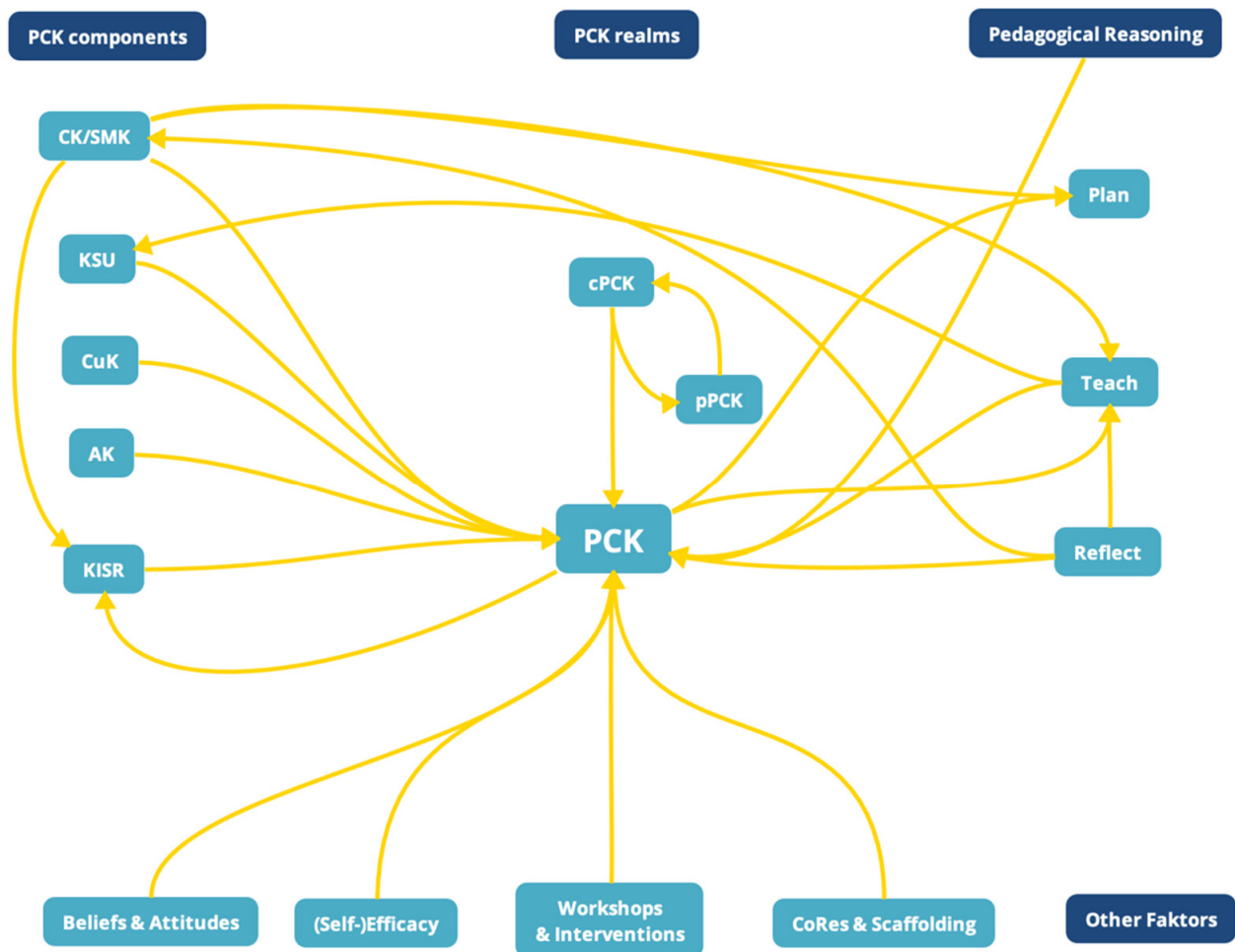


Figure 3. A map of the discussed effects in the field of science teachers’ PCK and their teaching practice.

In the $N = 132$ studies dealing with PCK and teaching practice, $N = 11$ studies directly identify effects of PCK (components) on teaching practice. Of those studies, $N = 6$ studies [55] found that PCK (in generic terms) has a positive effect on aspects of teaching practice, and in the other $N = 5$ studies, specific PCK components were found to have positive effects on teaching practice e.g., [56]. For teaching in a classroom situation, CK/SMK is considered essential in $N = 2$ studies e.g., [36]. Note also that some researchers e.g., [57] conclude that ‘content knowledge had positive influence on pedagogical content knowledge [and further that] content knowledge also influenced effective teaching practice’ [57] (p. 633). As a result of the researchers’ chained conclusions, any intermediate steps of implications may not be adequately represented in Figure 3.

Nevertheless, on the basis of our findings, it can be concluded that teaching in class is often ($N = 12$ studies) identified as a facilitator of development in PCK components e.g., [58,59]. A substantial proportion of the studies find reflection e.g., [18,60], workshops and interventions e.g., [61,62] as having positive effects on various PCK components ($N = 12$ and $N = 13$, respectively). Another aspect of practice is the interaction with the education community and/or colleagues (cPCK). A total of $N = 23$ studies find effects on PCK that are related to interactions with the community and/or colleagues. Finally, $N = 3$ studies describe a positive effect of different methods and materials on PCK that is credited to the pedagogical methods themselves e.g., [63], and $N = 5$ studies describe a positive effect of content representations, which is consistent with prior findings [23].

Focussing here on the ‘other factors’, it is interpretable that factors that relate to teacher state or trait-like variables (e.g., (self-)efficacy, beliefs & attitudes, personal concerns) amount to a total of $N = 13$ additional effects. These important statements are represented in the RCM as the amplifiers and filters.

In addition to the discussed effects of individual components, a total of at least $N = 79$ specific statements could be identified in the reviewed studies. For example, Nilsson [64] identified that collaborative reflection leads to a more professional PCK or the conclusion that PCK or its development is ambivalent [65,66]. Wang and Buck conclude that PCK development is a long-term and non-linear process [50], which might be beneficial and affect students’ outcomes e.g., [55]. Also, PCK seems to be better, if it is rich, flexible, and networked e.g., [37,64,67] and there is (probably) no maximum of PCK [68].

Evaluation Method

The initial search yielded $N = 1065$ articles (578 WoS, 300 ERIC, 94 PsycInfo, and 93 peDocs). The abstracts of all these articles were read using the criteria in Table 1 to identify the included articles, which resulted in a total of $N = 357$ studies for the review. In the screening phase that followed, the remaining articles were read in detail and $N = 132$ studies were selected for inclusion in the final systematic literature review. (A list of the reviewed Studies can be found in Appendix B.) The included studies were conducted in countries across six continents. Most of the studies were conducted in North America ($N = 43$; 32.6% of all studies), followed by Europe and Asia ($N = 32$; 24.2% each), Africa ($N = 14$; 10.6%), Oceania and Australia ($N = 9$; 6.8%), and South America ($N = 2$; 1.5%).

Information on coding units, coding methods, and interrater agreement as measured through Cohen’s κ for each RQ is displayed in Table 7. An example of the coding for each RQ is also provided. Note that interrater agreements for all RQs can be considered substantial or better [69].

Table 7. Coding unit, coding method and interrater agreement for all RQs.

Research Question	Coding Unit	Coding	Interrater Agreement
RQ1: Research Context	Abstract and/or methods section	- inductive coding of used methods - deductive coding of study design	$k = 0.97$
	Example: '(4) video stimulated-recall interviews conducted with teachers following each of these classroom observations' [46], p. 153 Coded as: (stimulated-recall) interview mixed-method design		
RQ2: Conceptualization of PCK	Abstract and/or theory section	- inductive coding of used PCK models	$k = 0.93$
	Example: 'Using the PCK model developed by Magnusson et al. (1999)' [70], p. 29 Coded as: Magnusson et al. (1999) [4]		
RQ3: Pedagogical reasoning in the teaching cycle	Section in which data collection framework was described	- deductive coding of the setting with regard to the teaching cycle	$k = 0.91$
	Example: 'The teachers reflected on their and their colleagues' experiences in implementing the new materials in their classes and of assessing them' [71], p. 194 Coded as: macro reflect		
RQ4: Discussed effects	Identifying the discussion section of all studies	- deductive coding of $N = 149$ derived effects	$k = 0.79$
	Example: 'The preservice teachers also attributed a substantial effect to the university-based workshop session on the development of their PCK' [58], p. 585 Coded as: effects of workshop/intervention on PCK-development		

4. Discussion

This study sought to characterise and synthesise research featuring science teachers' PCK and their teaching practice to advance our understanding of the explanatory capabilities of the RCM for science teachers' PCK [72] in the field of PCK research. Based on our review, prior results [23] can be largely confirmed. For example, researchers conceptualise and operationalise PCK quite differently according to a finite set of models. We were able to identify that often (in almost every third of the $N = 132$ studies), no well-established PCK model was used in the studies. Given the fact that most of the scaffolds used (e.g., Magnusson et al., 1999; Shulman, 1986; Park & Oliver, 2008) can be conceptualized with the help of the RCM of PCK, we tentatively conclude that the majority of PCK models can be captured by the RCM. With a focus on empirical findings from classroom-based research, the RCM as an interpretive tool may contribute to the understanding of the connections between PCK and teachers' practice. Here, it does not matter whether PCK is regarded as an integrative or a transformative construct because both are legitimate and possible. Even though 27.6% of the more recent studies do not use a specific PCK model or do not use a PCK model at all, the remaining 72.4% can be conceptualised with the RCM. In this way, the RCM could replace the frequently used (but possibly outdated) PCK models of Shulman (1986) or Magnusson et al. (1999) in the coming years. Furthermore, the RCM presents as a model that is suitable for a wide range of research foci. The RCM as a theoretical scaffold offers a robust baseline for communicating empirical findings within the community as well as beyond.

Our findings indicate that existing studies related to PCK and teaching practice used predominantly qualitative methods for analysing the relationships between PCK and teaching practice. This outcome is not surprising given that research emphasising the relevance of PCK for teaching a specific topic to specific students in a specific classroom has typically employed more qualitative approaches e.g., [36,58,61,73]. Furthermore, many researchers engage in data triangulation to grasp these complex constructs such as PCK and teaching practice. In their research designs, the majority of researchers used data collection

tools that help to capture teachers' pedagogical reasoning, or more specifically teachers' decision-making during teaching situations, and qualitative data analysis methods. Accordingly, these studies featured small sample sizes as researchers attempted to identify teachers' reasons for their classroom actions from rich and extensive bases of qualitative data. Elements of the micro teaching cycle were then brought into explicit focus rather infrequently, with more attention in general paid to the macro cycle. The pedagogical reasoning needed for teaching practice seems to manifest in the teaching cycle. With the trend towards larger samples, a tendency towards more quantitative research has also been observed here since 2020.

To acknowledge and facilitate research that addresses the networking of PCK components in classroom teaching, the RCM of PCK explicitly links PCK and teaching practice by depicting the teaching cycle (plan-teach-reflect) and pedagogical reasoning as a core of PCK. We found that many studies (also the studies not conceptualising PCK with the RCM) attended to at least one aspect of the teaching cycle in their research on PCK and teaching practice, and particular means of linking PCK and practice were found using research tools that focus on PCK in planning, enacting or reflecting. Data collection tools were often used that attempted to elaborate rationales for teachers' actions, and for this purpose, the aspects of the teaching cycle were addressed in different ways. It is notable that imbalances exist between studies investigating micro and macro teaching cycles, i.e., most realistic teaching studies refer to a macro level of the teaching cycle, whereas the few studies that refer to a micro level typically investigated simulated situations (e.g., in stimulated recall interviews). In summary, ePCK pPCK, and pedagogical reasoning appear to be closely interwoven and interconnected, which supports the claim that the interplay of networked PCK components with teachers' practical actions represents teachers' pedagogical reasoning and manifests in teaching cycles.

The analysis of the discussed effects of interactions between PCK and practice indicates that there is agreement in the literature that pronounced or rich PCK (e.g., teachers who scored highly in PCK measurement) or (networked) PCK components (e.g., teachers who scored highly in CK, PK and/or KSU performance tests or showed multiple interacting knowledge bases in interviews) are beneficial for effective teaching practice (based on verifiable evidence from sources such as classroom artefacts, students interviews, or observations). Furthermore, teachers' self-influencing factors (e.g., their interaction with the science education community and/or their pedagogical reasoning) as well as external factors (e.g., workshops/interventions) seem to be effective for PCK and PCK development. Based on these findings, it might be worthwhile to investigate science teachers' PCK development from a community of practice (CoP) perspective of [74] when considering the role of teachers' connectedness to their professional community. Analyses regarding RQ4 suggest that the implications of findings from the reviewed studies are multidimensional. Broad implications (like positive effects of well-developed PCK components on PCK and teaching practice) are more often discussed, and specific or consistent implications are mostly only indirectly considered.

5. Implications and Future Directions

The RCM of PCK provides a suitable lens for the investigation of PCK. It was modelled as a collective effort out of the tradition of PCK research and is able to represent a wide range of conceptualisations, study designs and research foci. These conclusions are confirmed by the identified acceptance of the RCM in the research community. In addition, the RCM allows the modelling of correlations between a teacher's PCK and the multiple components of PCK. We have summarised these opportunities of PCK development as teaching practice. Further, we conclude that teachers can develop their professional competencies from every aspect of their professional practice. Two groups of influences on PCK arising from teaching practice can be identified in the literature: first, teachers' interactions and participation in their teaching communities and second, self-influencing factors that are independent of a teacher's professional community and that only affect a single teacher. In sum, many of the

reviewed studies argue that PCK development is strengthened by teaching practice through (1) a teacher's own planning, teaching and reflection that is activated and sustained by pedagogical reasoning and (2) the teacher's interactions with colleagues and community. It remains to be evaluated which PCK components, if any, are most closely related to classroom performance. Due to the RCM, all these effects can be investigated based on the PCK components as integrative as well as transformative for the PCK or PCK components.

Limitations to our findings arise from the conceptual ambiguity associated with PCK in the literature and teaching practice and our commitment to the PCK tradition. We are also aware that PCK was first discussed as early as 1986 [15], but we have only used studies investigating interactions of PCK, PCK components and/or interactions of these with teaching practice that were available on the internet in our review. Our oldest studies were published in 2000. Also, our clear-cut boundary of pre- and post-RCM studies in the year 2020 is more pragmatically motivated than theoretically motivated, being based on when the first RCM was first mentioned in a published work. For example, we did not take into account submission deadlines or the durations of review processes.

However, we suspect that research on teachers' beliefs and motivational constructs might present further important insights into effective professional development programs that foster relevant competencies for teachers. These aspects were presumably less considered in the early studies on PCK as the construct of PCK itself first had to become established. To deepen understanding of the relationship between PCK and practice, we recommend that PCK components and realms be investigated in relation to each other, with due consideration of amplifiers and filters and the role of pedagogical reasoning in knowledge exchanges with and between realms of PCK. This review also revealed that, as in most PCK and practice research, there is a lack of quantitative research [32]. More quantitative research could enhance the generalizability and testability of PCK models. As of now, we consider PCK models as rather orientational frameworks. It is difficult to derive specific, operationalized hypotheses from most of them. Quantitative research may provide effect sizes to establish the importance of different factors that impact PCK development (see RQ4). Focused and quantitatively verifiable analyses of the interrelationships between the individual components are needed to strength understanding, and a unified framework model of PCK (like the RCM) would be very helpful for this.

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Appendix A

List of Abbreviations

PCK	pedagogical content knowledge
RCM	refined consensus model (of PCK in science education)
AK	assessment knowledge
CK	content knowledge
CuK	curriculum knowledge
CxK	contextual knowledge
KA	knowledge about assessment in science
KC	knowledge about science curriculum
KISR	knowledge about instructional strategies and representations for teaching science

KS	knowledge of students
KSU	knowledge about student understanding of specific science topics
OTS	orientations towards science teaching
PK	pedagogical knowledge
SMK	subject matter knowledge
STEM	science, technology, engineering, and mathematics
cPCK	collective PCK
pPCK	personal PCK
ePCK	enacted PCK
ePCKp	planning (in the micro and/or macro teaching cycle)
ePCKt	teaching (in the micro and/or macro teaching cycle)
ePCKr	reflecting (in the micro and/or macro teaching cycle)
CoRes	content representation
PaP-eRs	pedagogical and professional experience repertoires
CoP	community of practice

Appendix B

List of Reviewed Studies

- Akerson, V. L., Carter, I. S., Park Rogers, M. A., & Pongsanon, K. (2017). A Video-Based Measure of Preservice Teachers' Abilities to Predict Elementary Students' Scientific Reasoning. *International Journal of Education in Mathematics, Science and Technology*, 1–1. <https://doi.org/10.18404/ijemst.328335>.
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