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Research paper

Using longitudinal models to describe preservice science teachers' development of content knowledge and pedagogical content knowledge

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ABSTRACT

Cross-sectional studies have revealed the importance of university teacher education for science teachers' professional knowledge. However, a detailed understanding of the development of this knowledge is lacking. Our analysis addresses this gap by applying longitudinal models to elucidate how preservice science teachers' content knowledge (CK) and pedagogical content knowledge (PCK) evolve. Our results revealed a nonlinear growth for CK and PCK. We found that both interact during their development and that this interaction changes over the course of teacher education. Also, individual (grade point average) and institutional (teacher education program, second science subject) factors are related to their development.

1. Introduction

Teachers and teacher training are key factors for the quality of teaching and the learning success of students (Bromme, 1997; Lipowsky, 2006). Teachers affect students' performance differences as well as their performance-related personality development (Hattie, 2009; König et al., 2011). Teachers need a broad and robust knowledge base for successful teaching as knowledge as disposition is an important prerequisite for teaching performance (Blömeke et al., 2015).

Science lessons cover complex and diverse subject matter and make high demands on science teachers' content knowledge (Morell et al., 2020). Obtaining scientific literacy poses a big challenge for many students (e.g., OECD, 2019). To clarify the subject matter, make it comprehensible for students, and create a learning environment conducive to understanding science, teachers need a variety of different types of knowledge (e.g., Morell et al., 2020). Following Shulman's framework from 1986, these can be summarized as teachers' professional knowledge. Teachers' professional knowledge covers both generic (pedagogical knowledge: PK) and subject-related (content knowledge: CK; pedagogical content knowledge: PCK) domains.

The importance of teacher education for becoming a successful science teacher is repeatedly emphasized (Kind & Chan, 2019; Kleickmann et al., 2014; Morell et al., 2020; van Driel et al., 2002). However, the critical question in this context still is: How does professional knowledge develop? Respective findings so far are scarce (see also Abell, 2007; Sorge et al., 2019; van Driel et al., 2014). Existing cross-sectional data give insights into relationships between variables at a given point in time or into relative differences between groups or cohorts. Cross-sectional data, though, do not support inferences about developmental processes over the course of months or years. Thus, longitudinal studies are urgently needed to elucidate individual development and interindividual differences in intraindividual professional knowledge development (Allemann-Ghionda & Terhart, 2006; Schaefers, 2002). Our study aimed to address this need. We investigated the development of preservice science teachers' (here: preservice biology teachers as example) CK and PCK by analyzing the respective growth curves, identifying potential covariates, and considering the interactions of the constructs as they developed. The expected longitudinal findings can provide important information for improving teacher education at university. First of all, the description of growth itself helps to identify whether there are phases within the teacher education program in which more knowledge development takes place than in others. The identification of relevant covariates could help to advise and support students more individually depending on their profile (from individual entry requirements and the chosen teacher education program). Findings on the interplay between CK and PCK during development can provide

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empirical support for the long-standing demand to more closely interlink CK- and PCK-related courses in the teacher education program.

The following sections provide an introduction to the concept of content-related professional knowledge and provide an overview of the current state of research.

1.1. Professional competence of teachers

Successful teachers are characterized by different features that can be summarized under the term professional competence (Baumert & Kunter, 2013). Professional competence covers characteristics that help teachers to cope with the demands of teaching. The professional competence of teachers comprises four aspects (1) professional knowledge, (2) motivational orientations, (3) values, beliefs, and goals, and (4) self-regulative skills. The guiding principle here is that competence encompasses more than knowledge and, moreover, can be acquired in the course of professionalization (Weinert, 2001). Professional knowledge represents a relevant area of professional competence and is linked, for example, to aspects of lesson quality (Förtsch et al., 2017) and student performance (e.g., Mahler et al., 2017a). This aspect of competence is in the focus of this article.

1.2. Content-related professional knowledge: CK and PCK

Since Shulman's (1986) pioneering reflections on the knowledge base that makes teachers experts in their subject, three domains of knowledge have been described (1) CK, (2) PCK, and (3) pedagogical knowledge (PK; e.g., knowledge about classroom management). The first two domains, CK and PCK, are in the focus of this study and will be described in more detail below.

CK and PCK represent the content-related domains of teachers' professional knowledge (Gess-Newsome, 2015; Shulman, 1986) and reflect the central role of subject-matter in teaching and teacher education (Depaepe et al., 2013; Shulman, 1986). CK not only covers factual knowledge about a particular domain or subject matter (Ball & McDiarmid, 1989); teachers with profound CK also understand the structure of a domain, as well as essential principles and concepts within that domain (Shulman, 1986). CK is an essential prerequisite for providing lessons in an effective content-related learning environment for students. More precisely, teachers with profound CK can provide high-quality instruction (Käpylä et al., 2009) and cognitively activating lessons (Hashweh, 1987) that are well structured and problem-oriented (Hashweh, 1987; Shulman, 1986). CK helps teachers to develop teaching strategies that flexibly adapt to students' learning difficulties (Hashweh, 1987). Moreover, CK is directly linked to students' performance (Sadler et al., 2013). In this study we focused on the biological CK of (preservice) biology teachers related to the content areas genetics, morphology, physiology, ecology, and evolution.

PCK is a knowledge domain exclusive to the teaching profession (Shulman, 1986). In contrast to CK, the conceptualization of PCK is less uniform. Several researchers have attempted to conceptualize and define PCK. What all conceptualizations or models do have in common, however, is the reference to the ideas of Lee Shulman, who describes PCK as the knowledge necessary to teach a particular subject matter and make it understandable to students (Shulman, 1986, 1987). On the one hand, the internal structure of PCK is determined by content facets (for an overview of facets in various models and studies, see Kind, 2009). Although there are these many conceptualizations, which is definitely criticized (Ball et al., 2008), two facets are mentioned continuously (van Driel & Berry, 2010): (1) knowledge about instructional strategies and adequate representations (e.g., pictures, texts, models) and (2) knowledge about students' understanding (e.g., about misconceptions and learning difficulties related to specific content) (Großschedl et al., 2019; Lee & Luft, 2008; Park & Oliver, 2008; Schmelzing et al., 2013; van Driel et al., 1998). These two facets are also in the focus of this study. Furthermore, other models, such as the *Refined Consensus Model* (RCM; Carlson and Daehler, 2019), also refer to different types of knowledge. The RCM tries to condensate an intensive discussion about PCK and considers different realms (1) cPCK (collective PCK, i.e., the scientific canon), pPCK (personal PCK), and ePCK (enacted PCK). Within the RCM model, the PCK conceptualization in this study can be located in the pPCK realm when it comes to the test performance of the preservice teachers and in the cPCK realm concerning the underlying instrument (see Großschedl et al., 2019 for the instrument). In the RCM, as in Blömeke et al. (2015), it becomes clear that knowledge is the prerequisite for teaching action and, accordingly, its formation should be the focus of university teacher education (Schiering et al., 2021).

Shulman (1986) described PCK as the amalgam of content and pedagogy. This leads to the question how unique PCK as knowledge domain is and how its relation to the other knowledge domains is. Gess-Newsome (1999) describes (1) the integrative model and (2) the transformative model. The integrative model assumes that PCK as a unique domain does not exist but represents the integration of CK and PK. The transformative model describes PCK as a unique domain or the synthesis of CK and PK. The construction of the instrument used in the study is based on the assumption of a transformative model (cf. Großschedl et al., 2019), as empirical findings indicate a good fit here (e.g., Angeli & Valanides, 2009; Baumert & Kunter, 2013). PCK is understood as a unique domain of knowledge that is correlated with the other domains of professional knowledge.

PCK is an important predictor of students' performance (Mahler et al., 2017a; Sadler et al., 2013). Teachers with sound PCK have been found to provide high-quality instruction (Park et al., 2011; Roth et al., 2011), cognitively activating lessons (Keller et al., 2017; Kunter, Kleickmann, et al., 2013), and individual support for their students (Kunter et al., 2013). Moreover, they can choose adequate tasks and representations (Magnusson et al., 1999) and consider students' prior knowledge, learning difficulties, and learning goals (Magnusson et al., 1999).

Numerous studies have investigated whether (content-related) professional knowledge is a one-dimensional construct or whether the knowledge domains can be separated. The majority of studies come to the conclusion that CK and PCK can be represented as independent but correlated constructs (e.g., Großschedl et al., 2015; Copur-Gencturk & Tolar, 2022; Jüttner et al., 2013; Phelps & Schilling, 2004). This has important consequences for the development and validation of instruments as well as for the investigation of CK and PCK development. In the present study, we follow the assumption of independent but correlated knowledge domains.

1.3. Development of content-related professional knowledge

Teacher education at university has been described as being formative for the development of professional knowledge (Kleickmann et al., 2014; Prescott et al., 2013; Schiering et al., 2021; van Driel et al., 2002; Youngs & Qian, 2013; see also official documents: e.g., Morell et al., 2020).

Numerous studies have investigated the professional knowledge of preservice science teachers (e.g., Gess-Newsome, 1999; Nilsson & Loughran, 2012), preservice mathematics teachers (e.g., Schmidt et al., 2007; Youngs & Qian, 2013), preservice physics teachers (e.g., Riese et al., 2015; Schödl & Göhring, 2016; Sorge et al., 2019), preservice chemistry teachers (van Driel et al., 2002), and preservice biology teachers (e.g., Kleickmann et al., 2014; 2022; Jüttner et al., 2013; Kramer et al., 2021). Research on preservice teachers' professional knowledge can refer either to cross-sectional data or to longitudinal data; each data type allows for different research questions and findings. From cross-sectional research, information can be gained about individual and institutional factors that are related to preservice teachers' professional knowledge or can compare different cohorts from different semesters (e.g., Blömeke et al., 2008b; König and Blömeke, 2009). However, cross-sectional research is limited in that only correlational relationships can be presented, so ultimately the directions of the respective relationships remain unclear and can only be derived via theoretical assumptions. Longitudinal designs (as in the present study), on the other hand, have the advantage that the temporal sequence of the variables allows the investigation of the development of the respective variable and allows to better understand the directions of relationships. Thus, a longitudinal design provides a good starting point for examining the development of professional knowledge. Most of the available findings (see above) are gained from cross-sectional or cohort designs. The limited existing longitudinal findings hint at a growth in professional knowledge during teacher education at university (for PCK with a focus on lesson planning: Prescott et al., 2013; for PK with two measuring points: König, 2010; König and Seifert, 2012). Moreover, studies with a longitudinal design but a very small sample are available (Baer et al., 2007, 2011).

1.3.1. Teacher education in Germany

The study at hand is located in Germany. Teacher education in Germany is structured into three phases (1) teacher education at university, (2) a trainee teacher phase in schools with related further teacher education courses and (3) in-service learning. The teacher education programs are structured according to the German school system. On the secondary level, there is a distinction between schools qualifying their students for an academic career (academic track) and schools qualifying their students for a non-academic career (non-academic track).

Future teachers in Germany study two school subjects. The teacher education program is in particular structured into three areas: learning opportunities for (1) CK, (2) learning opportunities for PCK and (3) learning opportunities for PK. The learning opportunities for CK and PCK are differentiated according to the certain subject, while the learning opportunities for PK are subject-independent.

As a rule, the teacher education program lasts five years, with students earning a Bachelor's degree after three years and a Master's degree after two further years.

1.3.2. Individual and institutional factors related to preservice teachers' professional knowledge

Blömeke et al. (2008) introduced a multilevel model with different covariates for the development of professional competence. Beyond others, like systemic factors, individual and institutional factors are described. We focus on these two levels in our study.

Individual factors. Individual factors cover specific characteristics of a person. Considering individual factors is fruitful as the closer characteristics are to the learners, the easier it is to explain the variance in the outcome variable (Zeichner & Conklin, 2005). Often, these characteristics represent particular attributes of preservice teachers at the time they enter the first phase of teacher education (e.g., grades, gender, socioeconomic background; König, 2010). An essential assumption in educational research concerning entry conditions is that individuals with more favorable characteristics (e.g., good grades) benefit from this throughout their educational biography (Dannefer, 1987). Accordingly, an individual factor that plays a vital role in entrance to a teacher education program at university is the grade point average (GPA). In Germany, where this study was conducted, students receive a GPA when they reach the end of their school career and the GPA is the most important selection criterion for university education (Heine et al., 2006). It serves as a proxy for cognitive abilities (Riese & Reinhold, 2012). However, this description is not quite sufficient, as the GPA of course also refers to academic motivation, learning strategies, prior knowledge, so it is perhaps more appropriate to describe it as a proxy variable for academic ability. Previous research has suggested that the GPA in general might be a predictor of study success (Belfield & Crosta, 2012; Vulperhorst et al., 2018). This has also been reported for prospective teachers (Blömeke et al., 2008a; König, 2010; König and Seifert, 2012; Rothland, 2011). This is supported by the assumption that earlier education impacts later processes in education (Mayer & Tuma, 1990). Trapmann et al. (2007) even described the GPA as one of the strongest single predictors of academic success. Belfield and Crosta (2012) also found the school's GPA to be an excellent predictor of academic success as it explained 21% of the variance in the college GPA. Although most research in this field refers to a wide variety of university disciplines, some studies have investigated the relationship between the GPA and preservice teachers' professional knowledge. Those studies revealed a significant positive relationship between the GPA and the CK of preservice biology teachers (Großschedl et al., 2015) as well as the PCK of preservice physics teachers (Riese & Reinhold, 2012), preservice mathematics teachers (Kleickmann & Anders, 2013), and preservice biology teachers (Großschedl et al., 2015).

Institutional factors. Institutional factors represent the conditions formed by the university as an institution. Especially the type of teacher education program (König et al., 2016) and the second subject are associated with preservice teachers' professional competence (Welter et al., 2022). Preservice teachers can choose from teacher education programs, which are closely related to the German secondary school system. In particular, two types of teacher education programs can be distinguished (e.g., Blömeke et al., 2016). These focus on a teaching career either in academic-track or in non-academic-track secondary schools. Academic-track schools lead their students to the German equivalent of the high school diploma (the Abitur) and train them for university studies. Non-academic-track schools prepare their students, for example, for vocational education. The separate teacher education tracks differ in the number of content-related courses they comprise. Future academic-track teachers receive more learning opportunities concerning their CK than future non-academic-track teachers (Bauer et al., 2010; KMK, 2008; Neumann et al., 2017. The number of PCK-related learning opportunities is comparable between the two tracks (KMK, 2008). Some studies have revealed that academic-track teachers outperform their non-academic-track colleagues concerning CK (Großschedl et al., 2014; Schödl & Göhring, 2016), PCK (Riese & Reinhold, 2012; Sorge et al., 2019), or both (Kleickmann et al., 2013). The relevance of the teacher education program has been further demonstrated by the comparison of the professional knowledge of prospective elementary and secondary school teachers. Secondary school teachers outperformed their elementary school counterparts in terms of CK (Depaepe et al., 2015).

Preservice teachers can choose from a variety of second subjects. It is assumed that the profiles of preservice teachers who have different subjects differ (Roloff-Henoch et al., 2015). Transferring knowledge between two conceptually more closely related subjects seems to be more straightforward than transferring knowledge between two conceptually more distanced subjects (Welter et al., 2022); it also has a positive impact on the structure of cognitive networks of professional knowledge (Heitzmann, 2002). This assumption is based on the fact that the natural sciences share certain aspects (e.g., epistemological and methodological knowledge; Welter et al., 2022). Research concerning the impact of a second subject on professional knowledge is available for language subjects, mathematics, and science subjects. Blömeke et al. (2013) found that the professional knowledge of preservice teachers whose first subject was English did not benefit from having a second subject that was a language subject but, surprisingly, did benefit from having a second subject that was a science subject. Moreover, they found a negative relationship between preservice mathematics teachers' professional knowledge and a second subject that was a language or humanities subject. An earlier study (Blömeke et al., 2012) did not find any association between preservice mathematics teachers' professional knowledge and a second subject that was a science subject. Welter et al. (2022) found that preservice biology teachers who studied chemistry as second subject had higher CK and PCK than preservice biology teachers who had a different second subject.

1.4. Interplay of CK and PCK during their development

The early work of Lee Shulman already provides information on the interaction between CK and PCK. He describes PCK as an 'amalgam' or 'blending' of content and pedagogy (1987, p. 8), which initially indicates a fundamental connection. In addition, he describes CK as a source for PCK. It is important to note at this point that these were initially theoretical considerations that had not yet been tested with empirical methods at the time. Numerous studies on the empirical structure of professional knowledge then found that CK and PCK represent unique domains of knowledge (Groβschedl et al., 2014; Jüttner et al., 2013; Kleickmann et al., 2013; Krauss et al., 2008; Phelps & Schilling, 2004; Sorge et al., 2019), which correlate positively with each other (Groβschedl et al., 2014; König et al., 2016; Schödl & Göhring, 2016; Sorge et al., 2019).

These findings lead to questions about the interplay of these two domains during preservice teachers' development. CK has been described as a necessary but, on its own, not sufficient condition for the development of PCK (Kind & Chan, 2019). Schiering et al. (2021) further stressed the significance of CK for the development of PCK. They analyzed preservice physics teachers in terms of different teacher education programs and identified different clusters. They found that within a cluster with a small proportion of PCK-related courses, preservice teachers' PCK was strongly predicted by CK ($\beta = 0.45$; $p < 0.001$). Sorge et al. (2019) found that the relationship between CK and PCK changed over the course of teacher education at university. They compared the interplay between CK and PCK in beginner and advanced preservice physics teachers and found a stronger correlation between CK and PCK for the advanced group ($r = 0.60$, $p < 0.001$ [beginning preservice teachers] vs. $r = 0.89$, $p < 0.001$ [advanced preservice teachers]).

2. Research questions and hypotheses

1. Do CK and PCK develop over the course of biology teacher education? If so, how can we describe their development (linear vs. nonlinear growth)?

Referring to existing cross-sectional data (Kind & Chan, 2019; Kleickmann et al., 2013; Riese & Reinhold, 2012; Schödl & Göhring, 2016), we assumed that both preservice biology teachers' CK and PCK develops over the course of teacher education at university. The longitudinal approach taken in this study allows us to generate findings on the actual development of the constructs over time beyond the results of cross-sectional studies. Additionally, we examined the shape of CK's and PCK's growth over the course of university studies in an exploratory fashion, as no respective theoretical developmental model exist.

2. To what extent are the learning trajectories of the CK and PCK of preservice biology teachers related?

Because of its conceptual closeness to PCK (Shulman, 1986) and because CK is described as being either related to or being a prerequisite of PCK (Kind & Chan, 2019; Schiering et al., 2021; Schödl & Göhring, 2016; Sorge et al., 2019), we assumed that CK, in particular, would have an impact on the development of PCK. As available findings concerning the relationship between CK and PCK stem from cross-sectional findings only (i.e., no statements can therefore be made about the direction of effects) the role of PCK as a predictor should at least be considered.

3. How are the individual factor GPA and institutional factors (type of teacher education program and second subject) related to the CK and PCK growth curves of preservice biology teachers?

In line with previous findings from cross-sectional research, we assumed that both individual (Großschedl et al., 2015; Blömeke et al., 2008; Kleickmann & Anders, 2013; Rothland, 2011; König, 2010; Sadler & Tai, 2001) and institutional (Groβschedl et al., 2014; Kleickmann et al., 2013; Schödl & Göhring, 2016) factors are related to the growth curves of CK and PCK.

3. Methodology and methods

3.1. Data collection and participants

This study was part of the interdisciplinary and longitudinal project *Competence Development in Mathematics and Science Teacher Education* (KeiLa). The aim of it was to investigate the development of preservice science and mathematics teachers' professional knowledge during the first phase of teacher education. CK, PCK, and PK, as the domains of teachers' professional knowledge, form the basis for the structure of university courses in Germany (KMK, 2008; Neumann et al., 2017). The project was conducted from 2014 to 2017 at 25 universities in Germany. The aim of the survey across so many locations is to generate cross-institutional statements (cf. König, 2010). For a long time, a major criticism, particularly in German professional research, was that studies only referred to one location or region. This leads to a reduction in informative value and generalized statements cannot be made (cf. KMK, 2003). In the 4-h paper-and-pencil assessment data related to preservice teachers' professional knowledge and individual and institutional factors were collected annually in multiple cohorts at the beginning of the study year. Our sample consisted of 299 preservice biology teachers, who participated in the assessments up to four times ($N = 140$: 1 participation, $N = 61$: 2 participations $N = 85$: 3 participations $N = 14$: 4 participation). In German teacher education, a six-semester Bachelor's phase is followed by a four-semester Master's phase. We collected data from eleven semesters to cover both Bachelor's and Master's phase. Due to small sample sizes in semesters 9 and 11, we were not able to consider these semesters in the study. Accordingly, we considered data from the Bachelor's phase as well as the beginning of the Master's phase.

Their mean age on their first attendance was 21.36 years ($SD = 2.59$). Approximately a third of our sample studied a second science subject (31%). The majority of the participants (68%) were enrolled in an academic-track teacher education program and 29% were enrolled in a non-academic-track program.

The study was conducted in accordance with the Declaration of Helsinki, and no approval of the protocol by the local Ethics Committee was necessary. All participants participated voluntarily and gave their consent for inclusion prior to every assessment. The purpose of the study (longitudinal assessment of individual and institutional determinants of preservice teachers' development of professional knowledge) was explained in advance. The testing was carried out anonymously and proceeded in the familiar surroundings of university lecture halls, therefore causing no distress to the participating preservice teachers.

3.2. Instruments

To measure preservice biology teachers' CK and PCK, we used the CK-IBI (Großschedl et al., 2018) and the PCK-IBI (Großschedl et al., 2019). These instruments were developed within the framework of the project *Measurement of Professional Competencies in Mathematics and Science Teacher Education* (KiL; Kleickmann et al., 2014). A preliminary curriculum analysis identified relevant content and ensured curricular validity (Großschedl et al., 2018; 2019). In addition, this preliminary study also provided validity evidence in terms of intended test interpretations. Also, the empirical separability had been investigated and hints at CK and PCK as separate domains. The model on which the item development both for CK and PCK was based, considers 3 dimensions (1) the biological discipline (e.g., genetics) or a biological topic, (2) the facets of PCK (e.g., instructional strategies) and (3) the cognitive processes addressed by the items (apply and understand, remember and retrieve).

3.2.1. CK

The CK-instrument was developed considering the content areas defined in the German teacher education standards (KMK, 2019) and the areas identified in a curriculum analysis (Großschedl et al., 2018). Accordingly, we considered five facets of biological CK that play a role in preservice biology teacher education: (1) ecology, (2) evolution, (3) genetics, (4) morphology, and (5) physiology. Thirty-eight items covered these five content areas (e.g., *'Check which cell structures can be found in all living prokaryotic and eukaryotic cells (there is only one correct answer! Ribosomes and mitochondria/plasma membrane and vacuoles/plasma membrane and nuclear membrane/plasma membranes and ribosomes'*; Groβschedl et al., 2019). Nine items were semi-open, and 29 items were single- or multiple-choice items. Missing values were coded to zero. The items were scored dichotomously (0 = wrong answer, 1 = correct answer) or polytomously (0 = wrong answer, 1 = semi correct answer – partial credit, 2 = correct answer) with a coding manual. The person separation reliabilities—as a measure of internal consistency—were good ($CK_{WLE}[Rel] = 0.81$; $CK_{EAP/PV}[Rel] = 0.82$), as were the item-fit value ranges ($0.83 < CK_{MSQ}[Outfit] < 1.21$ and $0.91 < CK_{MSQ}[Infit] < 1.09$; see Preparing Data section for further details).

3.2.2. PCK

We aimed to capture two facets of PCK with the 34 items of the PCK-IBI (Groβschedl et al., 2019): (1) knowledge about instructional strategies and adequate representations (e.g., *'State the most important aspect that should always be addressed when models are used in biology classes in order to take the fundamental character of a model into account.'*; Groβschedl et al., 2019) and (2) knowledge about students' understanding (e.g., *'In introductory ecology classes, the 'ecological niche' notion is often difficult to understand for students. Explain why the complete scope of the notion of the 'ecological niche' is sometimes hard to grasp.'*; Groβschedl et al., 2019; Lee & Luft, 2008; Park & Oliver, 2008; Schmelzing et al., 2013; van Driel et al., 1998).

Item scoring resulted in some split items, leading to 40 items, of which 20 were open-ended, nine were semi-open, and 11 were single- or multiple-choice items. Missing values were coded to zero. The items were scored dichotomously (0 = wrong answer, 1 = correct answer) or polytomously (0 = wrong answer, 1 = semi correct answer – partial credit, 2 = correct answer) with a coding manual. The reliabilities ($PCK_{WLE}[Rel] = 0.76$; $PCK_{EAP/PV}[Rel] = 0.79$) and item-fit values ($0.74 < PCK_{MSQ}[Outfit] < 1.52$ and $0.9 < PCK_{MSQ}[Infit] < 1.17$) were also good (see Preparing Data section for further details of data preparation).

3.3. Analysis

Data were prepared using SPSS (Version 23). All statistical analyses were conducted using RStudio (Rstudio RStudio Team, 2021) with the following packages: TAM (item response theory fitting; Robitzsch et al., 2020, pp. 5–19) and lavaan (latent growth curve and cross-lagged modeling, Rosseel, 2012).

3.3.1. Preparing data

We aimed to measure the development of preservice teachers' professional knowledge annually. We thus reshaped the multiple-cohort data to a longitudinal design, with the preservice teachers assigned to their study years independent of the measuring points (sample sizes per study year 1: $n = 141$, 2: $n = 101$, 3: $n = 155$, 4: $n = 101$). The sample sizes in years 5 and 6 were too small for the analyses (5: $n = 48$, 6: $n = 8$).

The items of the knowledge tests were recoded to dichotomous and polytomous scores. We chose a partial credit model (PCM; Masters, 1982) and calculated weighted likelihood estimation (WLE) scores (Warm, 1989) using concurrent calibration to ensure the comparability of person scores across time points, i.e. all parameters from all time points were scaled on the same scale.

3.3.2. Linear and unspecified latent growth curve models

Two latent factors, that is, *intercept* and *slope*, are assumed to underlie the observed variables of each time point in latent growth curve models (LGCMs; Preacher et al., 2008). The intercept factor estimate gave us a measure of the first time point, thus, the starting point of the development, while the slope factor estimated the overall change over time. Slope factor loadings can be selected based on the hypothesized shape of the growth curve or can be estimated freely. Thus, LGCMs allowed us to (1) test hypotheses about specific types of trajectories (e.g., linear) and (2) obtain data-driven, unspecified trajectory models, which may result in nonlinear estimated slope factor loadings (Preacher et al., 2008).

It was in our interest to test whether a linear model was the best model to describe the knowledge growth in the CK and PCK of preservice biology teachers, referring to a constant knowledge growth. We thus compared each of the linear models for CK and PCK with a data-driven, unspecified trajectory model. Comparisons were carried out with chi-squared likelihood ratio tests (LRTs). If the data-driven models showed significantly better model-fit values than the linear models, slope factor loadings were fixed to those from the data-driven model for further analyses. Otherwise, the linear slope factor loadings were kept. Missing values were handled with full information maximum likelihood estimation. A detailed overview of LGCMs and model comparisons can be found in the Supporting Information.

3.3.3. Interplay between CK and PCK

Because CK and PCK correlate significantly in cross-sectional studies, their joint longitudinal development is of particular interest. To explore this issue, we chose two complementary approaches: a parallel process model (Preacher et al., 2008) based on latent growth curve modeling in order to obtain an overall trend, and a cross-lagged model in order to investigate the relationships between specific time points.

In the parallel process model, both the intercept and slope parameters of CK and PCK were related. Slopes were regressed on the opposite intercepts, whereas the slope and intercept of CK were correlated with the respective slope and intercept of PCK (Preacher et al., 2008).

In the cross-lagged model, PCK scores from later time points were regressed on the scores of their own previous time point and of the CK previous time point, and vice versa. Additionally, both scores of one time point were correlated for both knowledge domains.

3.3.4. Conditional models with time-invariant covariates

To identify relevant covariates for the growth parameters, we calculated conditional growth curve models. We considered three covariates related to (1) the individual factor GPA ($M = 2.06$, $SD = 0.56$) and (2) institutional factors (teacher education program and second subject). The intercept and slope parameters of each of the fitted CK and PCK LGCMs were regressed on the covariates separately and additionally simultaneously on all three covariates in a multivariate model, respectively.

4. Results

4.1. Development of CK and PCK

For both CK and PCK, nonlinear models showed the best model-fit values (see Tables 1 and 2 for model results and the Supporting Information for all model comparisons). For both CK and PCK, significant slope means (CK: $p < .001$; PCK: $p < .001$) and significant intercept variances (CK: $p < .001$, PCK: $p < .001$) were found, but the slope variances were near zero. Additionally, no covariances were found between the intercepts and slopes in the LGCMs (see Tables 1 and 2).

For CK, between 75.2% and 79.2% of the variance of the observed variables was explained by the latent growth factors. For PCK, values ranged from 67.4% to 71.7%.

Overall, the data-driven slope factor loadings in the LGCMs of both CK and PCK showed a nonlinear, flattening growth curve across time

Table 1
Model estimates of the full CK latent growth curve model with random intercept, random Slope, unspecified slope factor loadings, and intercept-slope covariance.

Parameter	Estimate	*SE*	*z* value	*p*
Slope factor loadings				
WLE_{CK} 1	0.00[a]	–	–	–
WLE_{CK} 2	1.00[a]	–	–	–
WLE_{CK} 3	1.38	0.13	10.57	<0.001
WLE_{CK} 4	1.74	0.18	9.82	<0.001
Means				
Intercept	−0.01	0.04	−0.31	0.76
Slope	0.44	0.05	9.22	<0.001
Variances				
Intercept	0.26	0.04	6.70	<0.001
Slope	0.01	0.02	0.52	0.61
Intercept-Slope Covariance	0.01	0.02	0.48	0.63

Note. Fixed slope parameters for a reference interval.

Table 2
Model estimates of the full PCK latent growth curve model with random intercept, random slope, unspecified slope factor loadings, and intercept-slope covariance.

Parameter	Estimate	*SE*	*z* value	*p*
Slope factor loadings				
WLE_{PCK} 1	0.00[a]	–	–	–
WLE_{PCK}2	1.00[a]	–	–	–
WLE_{PCK}3	1.64	0.19	8.56	<0.001
WLE_{PCK}4	2.13	0.26	8.29	<0.001
Means				
Intercept	−0.05	0.04	−1.14	0.254
Slope	0.34	0.05	7.31	<0.001
Variances				
Intercept	0.18	0.03	5.65	<0.001
Slope	0.02	0.02	1.07	0.287
Intercept-Slope Covariance	−0.01	0.02	−0.41	0.681

Note. Fixed slope parameters for a reference interval.

points, with the largest increase in the first interval.

4.2. Interplay between CK and PCK

A parallel process model resulted in a significant correlation between the CK and PCK intercept parameters ($r = 0.14$, $p < 0.001$). In accordance with the near-zero slope factors, no correlation was found between them. The intercepts were not found to have any significant influences on the opposite slopes of either CK or PCK. With the cross-lagged model (see Fig. 1), a significant correlation was found between the first time point of CK and that of PCK ($r = 0.46$, $p < 0.001$), corresponding to the correlation between intercept parameters in the parallel process model. This was not the case for any other time point. The cross-lagged paths revealed heterogeneous results (see Fig. 1). The CK scores of years 1 and 3 significantly predicted the subsequent PCK scores of years 2 and 4 in a positive way. Additionally, the PCK scores of year 3 showed a significant, positive, but small relationship with the CK scores of year 4.

4.3. Individual and institutional covariates

When added separately, GPA showed a significant relationship with initial CK and PCK scores as well as with the PCK slope (Models 1 and 5, see Tables 3 and 4). Looking at the institutional factors considered, teachers' type of education program also showed a significant relationship with CK and PCK intercepts, however, no relationship with CK and PCK slope factors was found (Models 2 and 6, see Tables 3 and 4). Being enrolled in a second science subject significantly predicted initial PCK scores (Models 3 and 7, see Tables 3 and 4). In the multivariate growth curve model for CK, GPA and teacher education program still predict initial CK scores significantly (Model 4, see Table 3), whereas in the multivariate PCK model, only the significant relationship between GPA and slope factor holds (Model 8, see Table 4).

5. Discussion

5.1. Development of CK and PCK

Overall, our results revealed that both CK and PCK developed positively over the course of teacher education at university. At first glance, this result is not surprising because teacher education at university is described as one source of teachers' professional knowledge (Grossman, 1990; Kunter, Kleickmann, et al., 2013). Many researchers have stressed the particular relevance of academic teacher education for the development of professional knowledge (Kleickmann et al., 2014; Schiering et al., 2021; van Driel et al., 2002; see also official documents: e.g., Morell et al., 2020; KMK, 2008) and the existing findings from longitudinal research also hint at a knowledge growth during teacher education (Prescott et al., 2013). A more detailed analysis revealed that participants started with different knowledge levels (i.e., significant intercept variance) but developed, on average, identically (i.e., nonsignificant slope variance) and that participants' intercept and slope factors were not related. It is important to mention that the non-significant slope variance does not indicate that there are no differences in the individual trajectories at all. Because a reliable slope variance in LGCMs is sometimes problematic to obtain (Brandmaier et al., 2018), we *t*-tested the mean structure for perfect correlations (i.e., testing the correlations of consecutive measurement points against 1, respectively). Perfect correlations would correspond to a small or zero slope variance in an LGCM. Our findings revealed that the order of persons differed significantly from time point to time point for both CK and PCK, which indicates that there were indeed interindividual differences in trajectories (for all: $p < 0.001$). The intercept variance was explained by the covariates GPA and type of teacher education program, which were related to

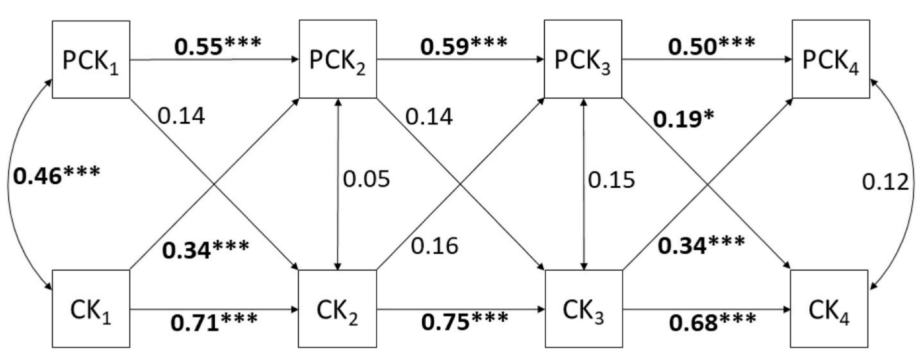

Fig. 1. Standardized results of the cross-lagged model with CK and PCK WLE values as observed variables. *Note.* Double-headed arrows refer to correlation coefficients, single-headed arrows refer to regression coefficients. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 3
Standardized regression weights of the conditional growth curve models for CK (Standard errors in parentheses).

	Model 1		Model 2		Model 3		Model 4	
	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope
CK								
GPA[a]	−0.44*** (0.07)	−0.26 (0.20)	–	–	–	–	−0.34*** (0.09)	−0.34 (0.24)
Teacher Education Program[b]	–	–	0.36*** (0.08)	0.00 (0.27)	–	–	0.20* (0.10)	−0.16 (0.24)
Second Subject[c]	–	–	–	–	0.14 (0.08)	0.54 (0.51)	0.07 (0.08)	0.33 (0.23)
R^2	0.20	0.07	0.13	0.00	0.02	0.29	0.23	0.20

Notes.[b] Negative relationships between growth factors and GPA refer to the type of GPA, where lower numbers mean better grades.
[b] Coding: 0 = non-academic track; 1 = academic track.
[c] Coding: 0 = not chemistry/physics, 1 = chemistry/physics.
*$p < 0.05$, **$p < 0.01$ ***$p < 0.001$.

Table 4
Standardized regression weights of the conditional growth curve models for PCK (standard errors in parentheses).

	Model 5		Model 6		Model 7		Model 8	
	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope
PCK								
GPA[a]	−0.26** (0.08)	−0.87*** (0.64)	–	–	–	–	−0.18 (0.10)	−0.97*** (0.63)
Teacher Education Program[b]	–	–	0.24* (0.09)	0.11 (0.18)	–	–	0.15 (0.11)	−0.27 (0.32)
Second Subject[c]	–	–	–	–	0.20* (0.09)	0.10 (0.19)	0.18 (0.09)	−0.03 (0.24)
R^2	0.07	0.76	0.06	0.01	0.04	0.01	0.12	0.77

Notes. [a] Negative relationships between growth factors and GPA refer to the type of GPA, where lower numbers mean better grades.
[b] Coding: 0 = non-academic track; 1 = academic track.
[c] Coding: 0 = not chemistry/physics, 1 = chemistry/physics.
*$p < 0.05$, **$p < 0.01$ ***$p < 0.001$.

the intercepts of CK and PCK and can be assumed to be proxy variables for performance at the beginning of teacher education. The lack of a correlation between the intercept and slope suggests that there is no Matthew effect (Dannefer, 1987) and that the growth in knowledge can be explained by variables related to teacher education (e.g., learning opportunities).

Additionally, to further understand the development of CK and PCK over the course of teacher education, a closer look at the respective growth curves is important as, to the best of our knowledge, research has not yet provided any findings about the growth of preservice teachers' CK and PCK as well as about especially formative phases within teacher education. This part of our study had a more exploratory character. As reported in the Methods section, we fitted multiple models with different assumptions (i.e., linear or nonlinear growth) related to the growth of CK and PCK. We found that nonlinear growth curves fitted the data best. This indicates that some periods of teacher education were more formative for the development of CK and PCK than others were. Our data revealed a steeper increase in the first year, which flattened out towards the later years. The strikingly strong increase in CK and PCK in the first year of study indicates that the study entry phase, in particular, seems to be significant for knowledge acquisition. However, the two curves differed in their magnitude, with the CK curve flattening more strongly and the PCK curve flattening less strongly in proportion to the first-year growth. In the case of CK, it can be assumed that, at the beginning of teacher education, there are still certain entrainment effects from the school years. It is known that CK acquired in school is a significant predictor of the development of CK at university (Sadler & Tai, 2001). PCK differs from CK in that there are no formal learning opportunities for PCK in school. On the contrary, one's own experiences in school could, instead, lead to misconceptions (Lortie, 1975). Accordingly, preservice biology teachers enter university with naïve PCK (Schiering et al., 2023), and the increase in PCK results from learning opportunities in university.

5.2. *The interplay between CK and PCK during their development*

The results revealed that the relationship between CK and PCK was much more complicated than we assumed. As discussed above, we found a relationship between the intercepts but not between the slopes and we did not find any influence of the intercepts on the opposite slopes in the parallel process model. This implied that CK did not have an impact on the overall shape of the development of PCK.

Also, the results of the cross-lagged model were mixed. When examining only one domain, we found that performance at one point in time predicted performance at the following point in time (i.e., autoregression). These results revealed a stronger relationship between the CK scores of different points in time compared to PCK. Thus, the orders of persons differed more strongly between PCK time points than between CK time points. This is in line with the difference in the explained variance of CK and PCK scores seen in the growth factors, as described above. An explanation for this could be that (considered across all participating universities) CK is taught somewhat canonically compared to PCK (Sorge et al., 2019). We further found that the CK measured in the first and third years predicted the PCK measured in the second and fourth years, respectively, and that the PCK scores of year 3 predicted the CK scores of year 4. Our results indicate that CK does represent a prerequisite for PCK. This is in line with previous research (Kind & Chan, 2019; Schiering et al., 2021; Schödl & Göhring, 2016; Sorge et al., 2019). In addition, the interaction of CK and PCK is also affected by the stability of the individual constructs. In our case, for CK less variance can be explained by additional factors as PCK. Additionally, we found that PCK predicted CK (although CK was a stronger predictor of PCK). A cautious explanation would be that prior PCK is related to CK because learning opportunities for applying CK in school contexts are present in PCK courses (there is often a significant proportion of PCK learning opportunities in the Master's degree program). Nevertheless, it is important to consider the small effect size here as well as the fact that the path coefficients were estimated using all available data (FIML), i.e., the estimation if each path coefficient is based on different participants' test scores. Accordingly, research is needed to replicate and better understand the connection. For example, it could be interesting to elaborate on the findings of Schiering et al. (2021) who found that PCK is especially dependent on CK in teacher education programs with a small proportion of PCK-learning opportunities.

5.3. Individual and institutional factors

The GPA as individual factor showed a significant relationship with the intercept of both CK and PCK, indicating that preservice teachers with a better GPA had higher intercept scores than those with a lower GPA. These results are in line with findings that have stressed the importance of the GPA (Großschedl et al., 2015; Belfield & Crosta, 2012; Blömeke et al., 2008; Kleickmann & Anders, 2013; Riese & Reinhold, 2012; Rothland, 2011) for teachers' professional knowledge.

The type of teacher education program and the second subject were considered as institutional factors. We found the type of teacher education program to be related to the intercept of CK and PCK. That means that preservice teachers who decided to apply for a teacher education program for future academic-track teachers outperformed preservice teachers who decided to apply for a teacher education program for future non-academic-track teachers with regard to their initial scores. A possible explanation for this could be that performance in school influences the decision regarding the teacher education program. The positive relation of the type of teacher education program to preservice teachers' professional knowledge is in line with previous findings (Großschedl et al., 2014; Depaepe et al., 2015; Kleickmann et al., 2013; Riese & Reinhold, 2012; Schödl & Göhring, 2016; Sorge et al., 2019). Although we also had assumed that we would find a relationship between the type of teacher education program—as an institutional predictor—and the slope, we were not able to find such a relationship. Additionally, for PCK, both GPA and teacher education program show no significant relationship with initial PCK scores when considered simultaneously. It could thus be the case that the consideration of the teacher education program actually incorporates a consideration of the GPA (due to the admission restrictions at universities).

Our results thus extend a mixed body of research (Welter et al., 2022; Blömeke et al., 2012; 2013). Maybe, examining the choice of the second subject in a more fine-grained manner (i.e., by regarding subject vs. a group of subjects) could help to clarify the significance of the combination of two science subjects in preservice teacher education. This is supported by Welter et al. (2022), who found that the transfer effects do not necessarily have to be reciprocal but, instead, that they depend on the role that the respective subject plays for the other subject (e.g., chemistry as a basic science for biology).

5.4. Limitations

First of all, it is important to mention that we used a convenience sample, as the students took part in the surveys voluntarily. A selection effect cannot be ruled out. Accordingly, the results as well as the significance testing should be interpreted with this in mind.

We collected data from eleven semesters to cover both Bachelor's and Master's phase. Due to small sample sizes in semesters 9 and 11, we were not able to consider these semesters in our LGCMs. Accordingly, our results only refer to a period between the beginning of teacher education at university (year 1) and the transition from bachelor to master (year 4).

We considered universities all over Germany for our analysis. The universities may differ in the design of their curricula or the scope of the learning opportunities presented. Nevertheless, an advantage of the German teacher education system is that national standards for teacher education exist (see also KMK, 2004, 2008, 2019). In these standards, CK and PCK (in addition to PK) are considered as structuring elements of teacher education. Moreover, in Germany, teacher education at university ends with standardized teaching degrees, which are valid in every federal state (except Bavaria), independent of the university from which the teaching degree was obtained. This makes it possible to model knowledge growth despite there being slight differences in the different curricula. One important reason for the consideration of 25 different universities all over Germany was to be able to make cross-institutional statements (cf. König, 2010). Nevertheless, a closer look at the mediating role of learning opportunities is an essential step for further research on this topic. Furthermore, it should be noted that we cannot say anything about individual knowledge development over the study period because the same individuals are not, or only to a very small extent, the same at the different measurement time points.

We considered two facets of PCK in our study (knowledge about instructional strategies and representations and knowledge about students' conceptions). As outlined in the theoretical background, there is an ongoing discussion which facets should be considered and different scholars described up to eight different facets. Accordingly, it is important to keep in mind that our statements only can refer to the PCK facets we consider in our study.

In the present study, the instruments were used repeatedly at all four measurement points. This may harbor the risk of retest effects. A retest effect is when test scores change due to repeated use. In such a setting, additional effects may play a role that are related to the test experience and not to the construct of interest (here: teacher education) (Salthouse & Tucker-Drob, 2008). One way to counteract this would be to offer different test variants or to set different cut-off values for test repetitions (Matton et al., 2011). As part of the study planning, we decided to use identical versions of the test in order to ensure the highest possible number of cases per item despite possible sample mortality. It should also be noted that a large number of the items (particularly in the PCK test) are open-ended and quite complex items and that the period between the measurement points was quite long (one year).

We did not test for longitudinal measurement invariance. That is, we did not investigate possible differences in item properties of the, in total, 72 items across the measurement occasions. Given the sample sizes in our study, this would have been a technically highly demanding task. Most likely, the standard error for the item parameters would have been too large to draw any meaningful conclusions. Still, we want to acknowledge that our conclusions are based on the assumption that the underlying construct remains comparable across time. A recent discussion on the implications of measurement invariance can be found in Robitzsch and Lüdtke (2023).

As a final point, it should be noted that a certain sample mortality is evident across the measurement points. This shows that in future studies even more emphasis must be placed on sample acquisition and sample retention.

5.5. Implications

5.5.1. Implications for teacher education

Our results provide initial indications of where improvement to teacher education programs could start.

CK and PCK both showed nonlinear growth over the course of teacher education, with the largest increase found in the first year of teacher education. These results indicate that the study entry phase is particularly important. Teacher educators should be aware of this special importance of the first year and should, accordingly, design the first learning opportunities with particular care. In order to maintain the above-mentioned CK entrainment effects beyond the first year of study, CK courses should perhaps offer further points of connection to the CK acquired at school.

We found an interplay between CK and PCK during their development, especially at the beginning of the teacher education program. Accordingly, we suggest that interdisciplinary learning opportunities should be provided for CK and PCK right at the beginning of teacher education. Maybe this would also strengthen the connection between CK and PCK in the later stages of teacher education. A stronger intertwining of these two domains in teacher education would be fruitful.

Due to the shortage of teachers in Germany, more and more people are coming into schools to teach as a second career. Ideally, this group of people should receive further training to prepare them for the teaching profession. Learning more about learning opportunities could also help to improve the development of persons with teaching as a second career. Learning more about what content and formats are beneficial can provide guidance on how to best support second career teachers with the reduced time available. Second career teachers often have in-depth CK, so it is particularly interesting to take a look at the learning opportunities for PCK.

Our study identified relevant covariates for the development of preservice biology teachers' CK and PCK and thereby revealed the importance of individual factors for CK and PCK. Primarily, the GPA represented a significant predictor of knowledge development. Our result thus cautiously underscores the importance of the GPA as an entry requirement.

5.5.2. *Implications for further research*

Following the implications for teacher education and in order to further understand the conditions under which content-related professional knowledge develops, a closer look at the learning opportunities provided at universities would be fruitful. A focus on the quantity and the quality (e.g., concerning cognitive activation or support) as well as on the content of the respective learning opportunities (Youngs & Qian, 2013) could give a detailed insight into the development of teachers' content-related professional knowledge. This is especially interesting as we found the first year of teacher education as especially formative. Learning more about learning opportunities could answer the question if the experiences during the first year in teacher education are important because of the timing or the characteristics of teacher education. In an investigation of learning opportunities, it is essential to consider the fact that there is a difference between the intended and the implemented curriculum. The results of Schiering et al. (2021) are interesting in this context, as they were able to identify different clusters for CK and PCK, taking into account the number of learning opportunities. They first show that CK predicts PCK. This correlation is particularly clear in the cluster with a low number of PCK learning opportunities. The PCK of participants from degree programs with a low proportion of science education is therefore more dependent on CK. In order to better understand the results of the cross-lagged model, it would be helpful in a next step to identify the proportions of learning opportunities across the locations. Schiering et al. (2021) also found a difference between the content areas specified in official standards and the content areas actually implemented in teacher education programs. Thus, research on learning opportunities for preservice biology teachers should focus on both curriculum analyses and learning opportunities. It is remarkable that we were able to model a consistent slope across so many different universities, despite the assumable different learning opportunities and sequences of learning opportunities available at each individual university. In a next step, however, a closer look should be taken at the context of case studies and, specifically, at the progress of individual students in connection with learning opportunities.

As our slope variance was not significant, we were only able to explain the average development (not the individual development). However, it is important to mention, that a non-significant slope variance does not mean, that all individual trajectories are the same but that the variance is too small to be detected in the growth model. Furthermore, the analyzation of the mean structure hints at possible individual differences. Accordingly, it would be interesting to further analyze whether there are different types of preservice teachers who differ in their growth and other characteristics (i.e., by conducting a latent profile analysis combined with latent growth curve models: growth mixture modeling). This could help to elucidate if and how teacher education is suitable for a heterogenous group of preservice teachers.

To learn even more about the development of preservice teachers it would be helpful to identify different competence levels and the respective knowledge facets loading on these levels. So far, we can only describe that development happens. But what this means in terms of content (i.e., which knowledge facets are acquired when) could be answered by such competence level models. Competence level models should be developed carefully related to a criterion-oriented validation process. Defining and justifying adequate thresholds is a further challenge.

We were able to model knowledge growth for preservice biology teachers over the first three study years. With respect to the year coverage, it would be interesting to investigate a more extended period of teacher education. Future research could specifically focus on the master phase and the transition phase to the second, more practical phase of teacher education. As more practical experience plays a role in these phases, an examination of knowledge development during them could provide valuable information. Questions related to the integration of knowledge domains and the development of action-related knowledge could be examined in those phases.

As mentioned at the beginning, successful teachers are not only characterized by their professional knowledge. In order to undertake a detailed investigation of the development of professional knowledge, we have limited ourselves to this aspect of professional competence in this study. However, future studies should definitely focus on other aspects of professional competence. Motivational orientations, for example, are related to both teacher characteristics as well-being (Keller et al., 2016) and student achievement (Mahler et al., 2018). Cross-sectional results already suggest that learning opportunities in teacher education (and work) play a role for motivational orientations (Mahler et al., 2017b). However, since the structure of the study program tends to focus on the acquisition of professional knowledge, the study of the development of motivational orientations over the course of study is particularly interesting.

Furthermore, the investigation should be extended to the generic area of professional knowledge, the PK. PK covers for instance knowledge about classroom management and knowledge about students' learning processes (Voss & Kunter, 2013) and develops over the course of teacher education (König, 2010; König and Seifert, 2012). Especially the interplay of the three domains of professional knowledge during their development is an interesting topic for future research.

Longitudinal data related to teachers' professional knowledge are rare (see also Abell, 2007; Riese & Reinhold, 2012; Sorge et al., 2019; van Driel et al., 2014). Within the KeiLa-framework, data are available for other science subjects as well as for mathematics. This "data treasure" provides the opportunity to learn more about possible synergy effects, namely, whether certain subject combinations are more effective for knowledge development than others. If data from other subjects (e.g., language subjects) were also considered, well-founded statements about fruitful subject combinations could be made. This would be a significant result for teacher education at university.

6. Conclusions

Our use of longitudinal data in the present study allowed us to make statements about the development of the CK and PCK of preservice biology teachers and in particular formative phases during teacher education programs, the interplay between CK and PCK as well about relevant covariates for the development. Our study thus represents a valuable extension to research on professional knowledge, in which—up until now—mainly cross-sectional research has been conducted. We have analyzed the data from preservice teachers at 25 universities so that we can make cross-institutional statements. Our results confirm the relevance of teacher education at university for the development of content-related professional knowledge. Especially, our results indicate that preservice biology teachers' first year in teacher education has a fundamental impact on their knowledge development and that CK and PCK are related during their development. Moreover, it should be emphasized that individual university entry requirements (e.g., GPA) play a role in preservice teachers' professional development, and, thus, should certainly be viewed as being relevant to successful entry into a teacher education program. In addition, the decision about the specific course of study (i.e., the decision in favor of or against a science second subject and the decision concerning the academic track or non-academic track) also has consequences for knowledge development.

The results of our study offer exciting starting points for future research on knowledge development among preservice teachers. In particular, a detailed look at the learning opportunities between the measurement points can provide further information on how preservice teachers develop and how they can be supported in the best possible way. In view of the prevailing shortage of teachers, this is a very important concern.

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Ethics approval statement

The study was conducted in accordance with the Declaration of Helsinki, and no approval of the protocol by the local Ethics Committee was necessary. The reason for this is that the testing was carried out anonymously and proceeded in the familiar surroundings of university lecture halls, therefore causing no distress to the participating preservice teachers.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

CRediT authorship contribution statement

Daniela Mahler: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Denise Bock:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Stefan Schauber:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Ute Harms:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to [The study is ongoing].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tate.2024.104583.

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