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Student teachers’ pedagogical content knowledge for teaching systems thinking: effects of different interventions

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ABSTRACT

Systems thinking has become increasingly relevant not only in education for sustainable development but also in everyday life. Even if teachers know the dynamics and complexity of living systems in biology and geography, they might not be able to effectively explain it to students. Teachers need an understanding of systems and their behaviour (content knowledge), and they also need to know how systems thinking can be fostered in students (pedagogical content knowledge (PCK)). But the effective development of teachers’ professional knowledge in teaching systems thinking is empirically uncertain. From a larger study (SysThema) that investigated teaching systems thinking, this article reports the effects of the three different interventions (technical course, didactic course and mixed course) in student teachers’ PCK for teaching systems thinking. The results show that student teachers’ PCK for teaching systems thinking can be promoted in teacher education. The conclusion to be drawn from our findings is that a technically orientated course without didactical aspects seems to be less effective in fostering student teachers’ PCK for teaching systems thinking. The results inform educators in enhancing curricula of future academic track and non-academic track teacher education.

ARTICLE HISTORY

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KEYWORDS

Pedagogical content knowledge; content knowledge; systems thinking; sustainable development; teacher education

Introduction

The meta-study of Hattie (2008) included numerous studies showing that the teacher is one of the most important factors in student learning. During the last 30 years, research in teacher education has searched for the essential characteristics possessed by a good teacher. Researchers have used three different paradigms: the teacher personality paradigm, the process-product paradigm and more recently the expert paradigm (Fischer, Borowski, & Tepner, 2012). Prior to their work, Shulman (1986, 1987) investigated teachers’ professional knowledge. Following recent research in teacher education (e.g. Abell, 2007; Borowski et al., 2012; Krauss et al., 2008; Kunter & Baumert, 2013), a theoretical distinction has often been drawn between pedagogical knowledge (PK) and content knowledge (CK) and pedagogical content knowledge (PCK). Current research in science teacher education highlight the content-related knowledge for effective teaching (Großschedl, Mahler,
Kleickmann, & Harms, 2014; Mahler, Großschedl, & Harms, 2017). Thus, one important role of science teacher education is to promote student teachers’ content-related knowledge, consisting of extensive CK and well-formed PCK. PK refers to the non content-related educational knowledge of strategies and procedures used to develop effective and undisturbed lessons. This kind of knowledge goes beyond the subject matter and was not a part of our study.

In the larger study, SysThema (systems thinking in ecological and multidimensional areas), we investigated in four substudies the effects of different interventions on aspects of student teachers’ teaching competencies in teaching systems thinking. The goal to promote systems thinking at school is based inter alia on the assumption that students can only actively participate in sustainable development when they are able to identify and to understand complex, global relations using the methods of system theory (Riess & Mischo, 2010).

Our consideration of systems thinking is based on the definition of Riess and Mischo (2010, p. 707):

We see systems thinking as the ability to recognize, describe and model (e.g. to structure, to organize) complex aspects of reality as systems. Another important aspect of systems thinking is the ability to identify important elements of the system and the varied interdependency between these elements. Other key aspects are the ability to recognize dimensions of time dynamics, to construct an internal model of reality and to make prognoses on the basis of that model.

Figure 1 provides a summary of the different substudies in the SysThema study. This article focuses on student teachers’ PCK for teaching systems thinking and presents the effects of the intervention. How we measured the dependend variable (declarative PCK)

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Student Teacher’s Content Knowledge in Teaching Systems Thinking</th>
<th>Student Teacher’s Pedagogical Content Knowledge in Teaching Systems Thinking</th>
<th>Student Teacher’s Reflective Content Related Knowledge in Teaching Systems Thinking</th>
<th>Student Teacher’s Epistemic Cognition in Teaching Systems Thinking</th>
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</table>

**Dependent Variable**
- Declarative Content Knowledge (CK)
- Declarative Pedagogical Content Knowledge (PCK)
- Reflective Content Related Knowledge (rCRK)
- Epistemic Cognition

**Independent Variable**
- Three Different Interventions
- Three different Interventions
- Three different Interventions
- Three different Interventions

**Measurement Instrument**
- Paper & Pencil Test
- Paper & Pencil Test
- Analysing a Video Vignette
- Portfolio

**Measurement Points**
- Pretest
- Posttest
- Follow-Up Test
- Pretest
- Posttest
- Follow-Up Test
- Pretest
- Posttest
- Follow-Up Test

**Figure 1.** Substudies in the larger study SysThema.
has been already discussed in detail in Rosenkränzer, Stahl, et al. (2016). The other sub-studies are not elaborated in this article.

**Theoretical background**

The distinction between the different forms of teachers’ knowledge has been widely accepted in research on that topic. The general understanding is that the three types of knowledge (PK, CK and PCK) can be hypothesised as representing conceptually distinct forms of knowledge (Abell, 2007; Borowski et al., 2012; Krauss et al., 2008; Kunter & Baumert, 2013). Numerous studies have indicated the essential need for CK in the development of PCK (Abell, 2007; Borko & Putnam, 1996; Großschedl et al., 2014; Grossman, 1990; Kunter & Baumert, 2013; Magnusson, Krajcik, & Borko, 1999; Park & Oliver, 2008; van Driel, Verloop, & de Vos, 1998). Accordingly, we briefly characterise the conceptualisation of teachers’ essential CK. One common aspect of all models in the literature is that they include an elaborated understanding of CK, which goes beyond common knowledge that any well-educated adult should have. Researchers, however, need to distinguish between static knowledge (e.g. ecological facts), declarative knowledge, which applies to concepts and principles within systems sciences, and procedural knowledge, which contains actions or manipulations that are valid within the systems sciences (De Jong & Ferguson-Hessler, 1996). Declarative knowledge includes, for example, basic knowledge of systems theory, knowledge of areas that can be considered as systems, knowledge of systems hierarchies and knowledge of properties of complex systems (see Figure 2). A system is defined as a ‘set of elements standing in interrelation’ (Bertalanffy, 1968, p. 55). The systems theory approach explains the behaviour of complex systems, for example, of ecosystems from a certain perspective. Procedural knowledge gained when solving problems by using system models includes how to assess whether a system model is useful for processing a present problem and whether a quantitative or a qualitative model is required, as well as providing explanations, making predictions and designing technologies based on these models. Another requirement in teachers’ CK is the ability to evaluate the validity of system models (e.g. in structure and in application) and the uncertainty of a prediction. How well a teacher knows the content ‘is central to their capacity to use instructional materials wisely, to assess students’ progress, and to make sound

<table>
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<tr>
<th>Competence Dimensions</th>
<th>Sub-Capability 1</th>
<th>Sub-Capability 2</th>
<th>Sub-Capability 3</th>
<th>Sub-Capability 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension 1: evaluation of system models</td>
<td>determining the structural validity of system models</td>
<td>determining the validity of system models</td>
<td>determining the validity of the application</td>
<td>determining the uncertainty of a forecast</td>
</tr>
<tr>
<td>Dimension 2: solving problems using system models</td>
<td>assessing the need of using a system model for processing a present problem</td>
<td>assessing the type of system model (e.g. quantitative vs. qualitative) that is required to process a problem</td>
<td>giving explanations, making predictions and designing technologies based on quantitative system models</td>
<td>giving explanations, making predictions and designing technologies based on qualitative system models</td>
</tr>
<tr>
<td>Dimension 3: modeling systems</td>
<td>determining system elements, interactions, subsystems, system boundaries, system hierarchies and the model purpose</td>
<td>understanding and reflecting a complex system with the help of a text field or a word model</td>
<td>reading and understanding qualitative system models, Construct influence diagram</td>
<td>reading and constructing quantitative system models</td>
</tr>
<tr>
<td>Dimension 4: declarative / conceptual systems knowledge</td>
<td>basic knowledge of systems theory (system concept, system structure, system behavior, sub-system)</td>
<td>knowledge of areas that can be considered as systems (also knowledge of simple and complex systems)</td>
<td>knowledge of system hierarchies (e.g., cell, tissue, organ, organism, population, biosphere, ecosystems, biosphere)</td>
<td>knowledge of properties of complex systems (structural and intrinsic complexity, non-linearity, emergence, ...)</td>
</tr>
</tbody>
</table>

**Figure 2.** Heuristic competence model in systems thinking.
judgments about presentations, emphasis, and sequencing’ (Ball, Hill, & Bass, 2005). It is not surprising then that several studies provide evidence for a positive relationship between teachers’ CK and their students’ learning progress (Abell, 2007; Baumert et al., 2009; Hashweh, 2005).

PCK ‘goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching’ (Shulman, 1986). Hence, PCK is the ‘result of a transformation of knowledge from other domains’ (Magnusson et al., 1999). But the core meaning of PCK is best explicated by Shulman’s original definition (1986), which states that PCK includes knowledge of students’ content-specific preconceptions and cognitions and knowledge of how to represent and comprehensibly formulate the content to others. The definition implies a transformation of CK into forms accessible to the students being taught. Research has identified components of PCK that are specifically important to successful teaching and that might therefore be used to conceptualise the PCK for teaching systems thinking (Abell, 2007; Borko & Putnam, 1995; Großschedl et al., 2014; Grossman, 1990; Kunter & Baumert, 2013; Magnusson et al., 1999; Marks, 1990; Park & Oliver, 2008; van Driel et al., 1998). Teachers possessing extensive PCK tend to use powerful forms of representations, analogies, illustrations, examples, explanations and demonstrations. PCK also includes the knowledge and understanding of what makes the learning of a special topic easy or difficult (Shulman, 1986). These components are essential parts of PCK and are included in almost every conceptualisation. Knowledge of curriculum and knowledge of educational ends are also considered in many conceptualisations of PCK. An overview of individual conceptualisations was provided by Park and Oliver (2008) and van Driel et al. (1998). Based on the approaches described and a detailed discussion in Rosenkränzer, Stahl, et al. (2016), we conceptualised PCK for teaching systems thinking in three facets as follows:

A central role in teaching systems thinking is the knowledge of curriculum and educational ends, which includes ‘teachers’ knowledge of the goals and objectives for students’ (Magnusson et al., 1999, p. 103). Even if Shulman (1986) and many other researchers (e.g. Großschedl et al., 2014) considered this knowledge to be a separate domain of the knowledge base for teaching (cf. curricular knowledge), we included it as a part of PCK in accordance with Abell (2007), Grossman (1990), and Magnusson et al. (1999). It represents structured knowledge teachers need for successfully teaching systems thinking, and it distinguishes the content specialist from the pedagogue. Hence, the teacher needs to know the competencies that they use for teaching (see Figure 2) and also the knowledge of how these competencies play a role in systems thinking. Peterson and Treagust (1995) found that knowledge of curriculum was an essential part of pre-service teachers’ pedagogical reasoning around lesson planning and instruction. The teacher, possessing a substantial PCK, knows the curriculum and educational ends for teaching a special topic.

The second facet is knowledge of instructional strategies, which includes the knowledge of methods as well as the ‘most powerful strategies’ (Shulman, 1986). Schmelzing et al. (2013) defined biology teachers’ knowledge of instructional strategies as which included knowledge about biology-specific instructions with illustrations, representations and analogies, knowledge of the appropriate use of biology-specific models of learning, knowledge of an appropriate use of biology-specific language, and knowledge of an appropriate use of scientific methods. Teachers need a repertoire of methods for promoting (Dimension 1) declarative and conceptual systems knowledge such as working with systems sciences
tasks or educational films usage about ecosystems and their integration in lessons. They know useful methods for teaching (Dimension 2) modelling systems as well as strategies and activities for promoting (Dimension 3) the use of system models to solve problems, and (Dimension 4) evaluation of system models (Rieß, Schuler, & Hörsch, 2015).

Knowledge of students understandings in systems thinking represents the third important facet of teachers’ PCK. Teachers need to work with students’ existing conceptions and prior knowledge. This ability requires the skill to discern ‘what makes the learning easy or difficult’ (Shulman, 1986) and empathic skills to discern a pupil’s correct and incorrect conceptions concerning systems thinking. Errors and mistakes can provide valuable insights into implicit knowledge of a problem solver. Thus being aware of typical student conceptions in the systems theory approach is important for teachers. Knowledge of students understanding requires a substantial and correct understanding of systems thinking (Abell, 2007).

The relevance of teachers’ PCK has been discussed in several studies, particularly in mathematics and science teaching (Ball, Lubienski, & Mewborn, 2001; Großschedl et al., 2014; Krauss et al., 2008). Current research on science teaching focusses on when and how science teachers PCK can be promoted.

In Germany, teacher education is divided into two clearly separated phases – a four- to five-year period of university-based education and a two-year period of classroom-based education (traineeship; German Referendariat). In the first phase of formal teacher education in the universities, a distinction is made between primary school teachers and secondary level teachers. In almost all German federal states (16 Bundesländer), pupils approaching the end of grade 4 are separated on the basis of their aptitude and ability to attend secondary tracks that prepare students for an academic university education (German Gymnasium; grades 5-12/13) or a non-academic education (German Hauptschule, Realschule, Sekundarstufenschulen; grades 5-10). Thus, secondary student teachers might decide to focus more on a technically oriented teacher education programme qualifying them to teach in academic track schools (German Gymnasium) or to focus more on a didactic-oriented teacher education programme qualifying them for the non-academic track (German Hauptschule, Realschule, Sekundarstufenschulen). All student teachers acquire a teacher certificate for at least two subjects (e.g. biology and geography). However, student teachers for the academic track receive courses with high demands for in-depth subject-matter knowledge, whereas student teachers for a non-academic track receive less courses in subject-matter knowledge and they focus more on pedagogy and didactic teaching methods (Baumert et al., 2009; Krauss et al., 2008). These two tracks arose out of different teacher education traditions and are of minor importance in empirical research. Nevertheless, the effective development of student teachers’ PCK, regardless of the track, remains empirically uncertain.

Based on this theoretical framework, we postulated the following three questions:

(1) Is there an intervention effect in student teachers’ PCK for teaching systems thinking?
(2) Are differences in the intervention courses identifiable?
(3) Is the technical course, the didactic course or the mixed course most effective in promoting student teachers’ PCK for teaching systems thinking?
Method

Study overview and research question

The goal of the present study was to evaluate effects of three different interventions in teaching systems thinking for student teachers at the Universities of Education in Freiburg and in Ludwigsburg (Germany) in the summer semester, 2013. We used a quasi-experimental approach (Shadish, Cook, & Campbell, 2002) with three treatment courses and a control group to examine effects of different inputs on student teachers’ PCK. Every course consisted of 14 units, of 90 min each (see Figures 3 and 4). All these courses had two common goals. First, the courses were intended to enhance student teachers’ ability in systems thinking, meaning their ability to solve complex dynamic problems within the context of sustainable development (acquiring CK). Second, the participants should gain the ability to effectively teach systems thinking in school (acquiring PCK). In Course 1, student teachers received a more technically oriented input. In Course 2, they received a more subject-related didactic input, and Course 3 combined technical- and subject-related didactic content in almost equal proportions. The control group received no intervention. We used these variations of the intervention to clarify which combination of technical- and subject-related didactic content helps the student teachers most effectively in teaching systems thinking.

This design opens the possibility to ‘test descriptive causal hypotheses about manipulable causes’ (Shadish et al., 2002). For each group, PCK for teaching systems thinking was...
measured before the intervention (test 1; t1) and after the intervention (test 2; t2). Two weeks after the intervention, we measured again in a follow-up test (test 3; t3). In all conditions we used the same pen and paper test (Rosenkränzer, Stahl, et al., 2016) as a measure of student teachers’ PCK. The entire survey time was about 2 hrs; the measurement of student teachers PCK was about 30 min. Participants received a compensation of 75 Euros for participation.

Based on our research questions and the study overview, we formulated our hypothesis as follows:

(1) Student teachers PCK for teaching systems thinking can be effectively promoted.
(2) There are significant differences between the intervention courses.

**Intervention**

Within the larger study, SysTheme, we designed three different courses for student teachers in the subject areas of biology and geography (described more in detail in Rieß et al., 2015). The didactic structure of all units in the intervention follows the model of problem-oriented learning and teaching, created by Rieß & Mischo (2017). At the beginning of each unit, the student teachers were introduced to the goals of the session and their importance. They began by working on a task, for example by analysing a complex problem within a genuine case example or creating an effective lesson about systems thinking. The student teachers became engaged in the given task, and while trying to solve the problem, they realised their need for further knowledge and competencies. The lecturer as an expert demonstrated the method developed by scientists to solve the problem and explained the thoughts behind each step. The student teachers were introduced into the expert culture by authentic activities and specific instruction. Over the unit duration, student teachers worked alone or in small groups on additional tasks that were similar to the first task while progressively learning to solve them independently. The results and the applied strategies were presented and reflected in class. One example is the marine overexploitation syndrome (Kropp, Eisenack, & Scheffran, 2006). It refers to the problem of overfishing in marine ecosystems based on short-term interests of globalised fishing industries. The core pattern of the overexploitation syndrome can be found in very different ecosystems all over the globe. Bossel (2007) published the concept of a ‘systems zoo’, a collection of about 100 simulation models categorised as (1) elementary systems, physis, engineering (2) climate, ecosystems, resources (3) and economy, society and global development. They may be used with the simulation software VENSIMPLE® (Personal Learning Environment, TM Verdana), which is free for educational purposes. Rieß et al. (2015) provided a detailed description of a learning environment on overfishing according to these teaching methods by using qualitative (syndromes) and quantitative system models that we tested in a seminar with student teachers.

In the first units, specific knowledge about systems was imparted in the following three topics: (1) introduction into systems sciences and analysis (Bossel, 2007; Matthies, Malchow, & Kriz, 2001); (2) forest ecosystem; and (3) syndromes of global change, for example deforestation, soil degradation, overfishing, climate change and overfishing according to the syndromes concept (Schellnhuber et al., 1997). Later in the courses,
the case examples of systems modelling, systems analysis and lesson planning were related to these topics. After providing a common foundation, the three courses diverged with regard to their technical- and subject-related didactic proportions.

**Intervention 1 – technical course**

In the technical course, the different systems were modelled and analysed with increasing autonomy and on a higher level of systems science. For example, the student teachers learned to construct an influence diagram such as a qualitative system model, consisting of system elements (nodes) and system relationships (influences, arrows). Quantitative system models were also constructed and simulated with software. The student teachers learned to analyse complex systems (e.g. the problem with overfishing; Kropp et al., 2006), to be able to provide explanations and to make predictions with regard to the behaviour of a system and to find appropriate measurements to influence the system behaviour in a positive way (e.g. calculating fishing quotas for sustainable fishing in a fishery model; Bossel, 2007). Furthermore, the student teachers evaluated system models, determined their validity and developed an awareness of their uncertainty. The students determined the sensitivity of the system model and created a range of possible future scenarios, and then they tested their implications by running the simulation under different conditions. How to foster pupils’ systems thinking in school and how to create an appropriate learning environment were less of a focus in the technical course.

**Intervention 2 – didactic course**

The more subject-related didactic course emphasised the effective teaching and learning of systems thinking in school. The student teachers approached the question of what is actually meant by systems thinking. They compared and reflected on different conceptualisations found mainly in the German literature (e.g. Riess & Mischo, 2010). The reasons for teaching systems thinking to pupils were discussed in depth. The participants formulated learning goals on different levels, compared them with the existing competence model (see Figure 2; cf. Rieß et al., 2015) and created different tasks for measuring the competence of systems thinking. The student teachers learned about several teaching methods (e.g. Schuler, 2012), tested them and planned numerous lessons. Scientific methods were considered, implemented and reflected on as possible teaching methods. They also learned about pupils’ preconceptions of systems (e.g. Jelemenská & Kattmann, 2008), and they thought about how to promote learning by engaging the pupils. Systems modelling and analysis received less attention and was practiced mostly with qualitative system models. The student teachers worked with fewer case examples and were more guided throughout the process. For example, they operated with simpler, ready-made simulation models on the computer. Most importantly, the participants adopted the perspective of a teacher and evaluated, for example, the impact analysis as a potential teaching method.

**Intervention 3 – mixed course**

The third courses combined technical and subject-related didactic content in almost equal proportions. The Mixed Course was designed from central components out of both
courses described above. The participants almost worked on the same level of systems science as the student teachers in the technical course, but they mostly used only one case example. They had less opportunity to practice systems thinking autonomously and to transfer their knowledge to other domains. Furthermore, they evaluated system models only slightly and reflected a little on the validity and limits of the models. However, the mixed course included sessions on conceptualisations of systems thinking, on a competence model, teaching methods and pupils’ preconceptions. The participants in this course had little time to work with the teaching methods or to practice, reflect and integrate them in planned lessons.

Participants

We offered courses in geography and biology at universities of education in Germany. These courses were essential seminars curriculum for student teachers and were labelled without describing any specific information about the content. The participants (108 student teachers) selected the intervention courses blindly. All the participants had earned the German Abitur (A-level degree qualifying for university admission), studied on average in their 6th semester, and were aged between 20 and 47 years. Table 1 displays the descriptive statistics (grade, sex, age and semester), which do not differ significantly between the courses. The low representation of males corresponds with the usual proportion of female and male student teachers in German universities of education.

Instrument

We developed a paper and pencil questionnaire to measure PCK for teaching systems thinking by using the heuristic competence model in systems thinking for item construction (Rosenkränzer, Stahl, et al., 2016). We decided to use open-ended items and transform the qualitative data into quantitative data by using a coding scheme according to Mayring (2007). This analysis belongs to the statistical mixed-methods analysis and represents a hybrid analysis using qualitative and quantitative methods. Closed tasks appear to be an inappropriate means to measure PCK, because only correct or incorrect explanations to explain teachers PCK exist (Krauss et al., 2008). Furthermore, some researchers criticise this closed framework because of the missing possibility of an independent critical thinking spirit (Haertel, 1991) and the weakness in capturing teachers’ creativity and originality (Schmelzing et al., 2013). We derived criteria for correct notes from previous research on PCK and the theoretical considerations of our heuristic competence model in systems thinking. Based on this devised coding scheme, three trained student assistants and the first author categorised the notes. Every correct comment

<table>
<thead>
<tr>
<th>Table 1. Sample of the intervention.</th>
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<tr>
<td>Control group</td>
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<tr>
<td>N</td>
</tr>
<tr>
<td>Male/female</td>
</tr>
<tr>
<td>Ø grade</td>
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<tr>
<td>Ø age</td>
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<td>Ø semester</td>
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was scored 1 and false answers were scored 0. Thus the maximum possible score was 13. After a few codings and some adaption of the coding scheme, we reached an acceptable interrater reliability (Krippendorff’s alpha over .80 [Hayes & Krippendorff, 2007]). We used IBM SPSS Statistics v.22 for computation of further analyses. The following paragraph provides more detail of our questionnaire (for a detailed discussion see Rosenkränzer, Stahl, et al., 2016).

We captured the Knowledge of curriculum and educational ends with five items. Four items focus on the competences and educational ends in orientation to the heuristic competence model in systems thinking. The fifth item asks for appropriate procedures to evaluate systems thinking (Figure 5).

Knowledge of instructional strategies for promoting systems thinking was also measured by five items. Four items ask for suitable or unsuitable methods and instructional strategies in each of the mentioned dimensions of the heuristic competence model and requires that respondents justify their decisions. The fifth item shows a well-known method for teaching systems thinking, which is then evaluated by the respondent.

**Figure 5.** Excerpt of the questionnaire to capture student teachers knowledge of curriculum and educational ends (translated only for publication – original in German language).
Further items captured the Knowledge of students’ understandings in systems thinking. In two of the items, we presented a statement from a pupil about systems (see Figure 6) and ecosystems. Participants were asked to assess this statement as correct, partially correct or false, and to justify their assessment. The third item showed a system model created by a 6th grader, which participants also assessed. The tasks include taking a professional point of view and evaluating correct and incorrect elements and relationships in this system model.

**Data analysis**

The questionnaire was psychometrically evaluated. We took care to satisfy content validity, and we submitted the questionnaire to experts (researchers in the didactics of biology and geography). According to the experts’ suggestions, we improved the measurement instrument by adding an introduction in the beginning of the questionnaire and ensured an adequate content validity. As an indicator for the convergent validity, we analysed expected correlations between PCK and CK questionnaires (Fanta, Bräutigam, & Riess, 2016). The correlation between these two forms of teachers’ professional knowledge was moderate ($r = .541, p < .01^{**}$), indicating a related but different form of knowledge measured (Trochim, 2000).

The data of the pretest indicated poor internal consistency. Notwithstanding, student teachers’ PCK could not be obtained before the intervention. Thus, our experts encouraged to recalculate the reliability after the intervention. The reliability of the overall questionnaire increased to a satisfactory level (Cronbach’s $\alpha = 0.80$ [Cronbach, 1951]). The reliability of Knowledge of students understanding in systems thinking is noteworthy. Items in this facet do not allow any variation (see Figure 6).

One student teacher marked the pupil’s statement as correct and justified the decision as follows:

*Figure 6.* Item 11 to capture student teachers’ knowledge of students’ understandings in systems thinking (translated from German only for publication).
Sie geht nach einem gewissen System vor, damit sie eine Email schreiben kann, würde sie dieses nicht befolgen, könnte sie weder eine Email schreiben, noch diese versenden. (OCES11)

English translation: She proceeds with a certain system, so that she can write an e-mail. If she did not follow in this manner, she could neither write an email nor send it.

This answer shows the student teachers’ deficient understanding of a system, which could be the reason for not seeing the pupil’s misconception about a system. For further analysis, this answer was scored with 0 points. Another student teacher marked the pupil’s statement as false and justified the decision with the following conclusion:

Bei einem System handelt es sich nicht um ein wie oben beschriebenes Rezept, sondern viele Faktoren spielen zusammen + beeinflussen (alle anderen Lebewesen/Räume des Systems (ACIS03)

English translation: A system is not structured as described, but many influential factors interact between all living beings/areas within a system

This justification demonstrates the student teachers knowledge about students understanding about systems. Thus, this student teacher would more likely address the misconception in subsequent lessons. Therefore we scored this answer with 1 point for further analysis.

Participants briefed about the intervention could have answered correctly, even if they lacked the required knowledge. Nevertheless, we included items in this facet that assessed an overall understanding of a system given the internal validity and the overall satisfactory reliability of the questionnaire.

The focus of this article is on the quantitative results. The data from the questionnaire were coded and processed using IBM SPSS Statistics v. 22 for Windows. Analyses focused on student teachers’ improvement in their PCK for teaching systems thinking. To test whether the four conditions in the experiment differed a priori in PCK, a univariate analysis with the dependent variable PCK at time \( t_1 \) and the independent variable ‘experimental condition’ was computed (Brown & Forsythe, 1974). Levene’s test showed a statistically significant difference in the error variances between the courses, \( F(3,104) = 3.86, p = .012 \). Given the different types of knowledge acquisition in the three different courses, we computed analyses of covariate (ANCOVA) in further analyses.

Results

(1) Is there an intervention effect in student teachers’ PCK for teaching systems thinking?

To test the central hypotheses, we assessed student teachers’ PCK for teaching systems thinking at three measurement points. We calculated an ANCOVA with the dependent variable PCK score at measurement \( t_2 \) (posttest) and in a second step at measurement \( t_3 \) (follow-up test). As covariate, we used the score measured in the pretest. The experimental condition was the independent variable with the three different courses and the control group. Before the intervention, student teachers reached a mean score of \( M = 3.28 \) (\( SD = 1.93 \)) which increased to \( M = 6.60 \) (\( SD = 2.75 \)) after the intervention. In the follow-up measurement, the analysis revealed the same results \( M = 6.50 \) (\( SD = 2.67 \)).
These values show a significant increase from pre- to posttest, along with a high effect, $F(3,103) = 22.71$, $p < .001$, $\eta^2 = .40$ and a significant increase to the follow-up test, $F(3,103) = 26.00$, $p < .001$, $\eta^2 = .43$. These results demonstrate that a significant improvement occurred in student teachers’ PCK for teaching systems thinking. Table 2 provides an overview of the overall findings.

(2) Are differences in the intervention courses identifiable?

The second research question examined the most effective course for increasing student teachers’ PCK in promoting systems thinking. We used a dependent-samples $t$ test to examine the difference between the pretest ($t_1$) and the posttest ($t_2$) and between the pretest ($t_1$) and the follow-up test ($t_3$). We also reported Cohen’s $d$ as the effect size for all $t$ tests and $\Delta d$ as a reference value of increase in comparison to the control group. The results of the simple main effects are summarised in Table 3 for the posttest and Table 4 for the follow-up test.

The results in Table 3 show significant differences in all treatment groups as well as in the control group. According to Cohen (1988), effect sizes between 0.5 and 0.8 reflect a medium effect and above 0.8 a large effect. Hence, even the control group had a large effect from pretest ($t_1$) to posttest ($t_2$). But these effect sizes should be interpreted with caution, because completing the same paper and pencil test more than once is associated with a learning effect. The effect of the intervention is better interpreted according to the difference of the effect sizes in each course compared to the effect size of the control group. The technical course scores increased by $M = 3.73$ ($SD = 3.31$) with an effect size of $d = 1.70$ in comparison to the control group with an increase of only $M = 1.44$ ($SD = 1.60$) and an effect size of $d = 0.80$. The interventions effect is the difference between the effect sizes, $\Delta d = 0.90$ (Bortz & Döring, 2006). The highest effect could be found in the Didactic Course with $\Delta d = 1.19$. In the mixed course, the effect was $\Delta d = 1.16$.

The analysis with the third measurement (follow-up) revealed a similar pattern. The control group had a large effect $d = 0.95$. The technical course and the didactic course achieved a higher effect, but the main effect of the mixed course decreased.

(3) Is the technical course, the didactic course or the mixed course most effective in promoting student teachers’ PCK for teaching systems thinking?

The effect size analysis does not indicate whether the course with the highest effect differs significantly from the other intervention groups. Only with a significant

Table 2. Overall findings of the intervention.

<table>
<thead>
<tr>
<th></th>
<th>Pretest</th>
<th>Posttest</th>
<th>Follow-up test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$ ($SD$)</td>
<td>Min/max</td>
<td>$M$ ($SD$)</td>
</tr>
<tr>
<td>PCK</td>
<td>3.28 (1.93)</td>
<td>0/10</td>
<td>6.60 (2.75)</td>
</tr>
<tr>
<td>Knowledge of curriculum and educational ends</td>
<td>1.19 (0.85)</td>
<td>0/4</td>
<td>2.70 (1.23)</td>
</tr>
<tr>
<td>Knowledge of instructional strategies for promoting systems thinking</td>
<td>1.39 (1.00)</td>
<td>0/3</td>
<td>2.57 (1.19)</td>
</tr>
<tr>
<td>Knowledge of students understandings in systems thinking</td>
<td>0.70 (0.77)</td>
<td>0/3</td>
<td>1.32 (0.91)</td>
</tr>
</tbody>
</table>

Note: The maximum PCK score to reach in questionnaire was 13.
increase compared to the other groups, can the course be interpreted as the most effective intervention in promoting student teachers’ PCK in teaching systems thinking. Therefore, we conducted a series of ANCOVAs with the independent variable of only two courses and the pretest score as covariate (see Table 5). We reduced alpha to minimise Type I errors because of the multiple hypotheses tests. (95% $\alpha = .05/3 = 0.016$; Bortz & Döring, 2006).

The results showed significant differences in student teachers’ PCK for teaching systems thinking between every single experimental condition and the control group. Further results revealed that the improvement of the technical course and the didactic course marginally failed the statistical difference in posttest, $F(1,45) = 6.02, p = .018, \eta^2 = .12$, but differed significantly in the follow-up measurement, $F(1,45) = 14.09, p = .000***, \eta^2 = .24$. However, we cannot yet rule out the possibility that this finding is simply the result of differences that exist between the groups. We could not find any statistical differences between the mixed course and the technical course or between the mixed course and the didactic course.

<table>
<thead>
<tr>
<th>Table 3. Main effects of posttest (t2).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre $M (SD)$</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Control group</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
<tr>
<td>Course 1 – technical</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
<tr>
<td>Course 2 – didactic</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
<tr>
<td>Course 3 – Mixed</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4. Main effects of the follow-up test (t3).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre $M (SD)$</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Control group</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
<tr>
<td>Course 1 – technical</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
<tr>
<td>Course 2 – didactic</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
<tr>
<td>Course 3 – mixed</td>
</tr>
<tr>
<td>Facet 1</td>
</tr>
<tr>
<td>Facet 2</td>
</tr>
<tr>
<td>Facet 3</td>
</tr>
</tbody>
</table>
Table 5. Results of the ANCOVA analysis in pairs.

<table>
<thead>
<tr>
<th></th>
<th>Pretest → Posttest</th>
<th></th>
<th></th>
<th></th>
<th>Pretest → Follow-up test</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{\text{Gain}}$ (SD)</td>
<td>df</td>
<td>$F$</td>
<td>Sig</td>
<td>$\eta^2$</td>
<td>$M_{\text{Gain}}$ (SD)</td>
<td>df</td>
</tr>
<tr>
<td>Control group vs.</td>
<td>1.44 (1.60)</td>
<td>$F_{\text{Pre}}$ (1,57)</td>
<td>0.98</td>
<td>.326</td>
<td>.017</td>
<td>1.40 (1.51)</td>
<td>$F_{\text{Pre}}$ (1,57)</td>
</tr>
<tr>
<td>Course 1 – technical</td>
<td>3.73 (3.31)</td>
<td>$F_{\text{Course}}$ (1,57)</td>
<td>18.72</td>
<td>.000</td>
<td>.247</td>
<td>3.44 (2.89)</td>
<td>$F_{\text{Course}}$ (1,57)</td>
</tr>
<tr>
<td>Control group vs.</td>
<td>1.44 (1.60)</td>
<td>$F_{\text{Pre}}$ (1,59)</td>
<td>22.77</td>
<td>.000</td>
<td>.278</td>
<td>1.40 (1.51)</td>
<td>$F_{\text{Pre}}$ (1,59)</td>
</tr>
<tr>
<td>Course 2 – didactic</td>
<td>4.75 (2.17)</td>
<td>$F_{\text{Course}}$ (1,59)</td>
<td>51.69</td>
<td>.000</td>
<td>.467</td>
<td>4.75 (2.17)</td>
<td>$F_{\text{Course}}$ (1,59)</td>
</tr>
<tr>
<td>Control group vs.</td>
<td>1.44 (1.60)</td>
<td>$F_{\text{Pre}}$ (1,57)</td>
<td>23.58</td>
<td>.000</td>
<td>.293</td>
<td>1.40 (1.51)</td>
<td>$F_{\text{Pre}}$ (1,57)</td>
</tr>
<tr>
<td>Course 3 – mixed</td>
<td>4.60 (2.01)</td>
<td>$F_{\text{Course}}$ (1,57)</td>
<td>45.05</td>
<td>.000</td>
<td>.441</td>
<td>4.26 (2.28)</td>
<td>$F_{\text{Course}}$ (1,57)</td>
</tr>
<tr>
<td>Course 1 – technical vs.</td>
<td>3.73 (3.31)</td>
<td>$F_{\text{Pre}}$ (1,45)</td>
<td>1.78</td>
<td>.189</td>
<td>.038</td>
<td>3.44 (2.89)</td>
<td>$F_{\text{Pre}}$ (1,45)</td>
</tr>
<tr>
<td>Course 2 – didactic</td>
<td>4.75 (2.17)</td>
<td>$F_{\text{Course}}$ (1,45)</td>
<td>6.02</td>
<td>.018</td>
<td>.118</td>
<td>4.75 (2.17)</td>
<td>$F_{\text{Course}}$ (1,45)</td>
</tr>
<tr>
<td>Course 1 – technical vs.</td>
<td>3.73 (3.31)</td>
<td>$F_{\text{Pre}}$ (1,43)</td>
<td>2.09</td>
<td>.156</td>
<td>.046</td>
<td>3.44 (2.89)</td>
<td>$F_{\text{Pre}}$ (1,43)</td>
</tr>
<tr>
<td>Course 3 – mixed</td>
<td>4.60 (2.01)</td>
<td>$F_{\text{Course}}$ (1,43)</td>
<td>3.49</td>
<td>.068</td>
<td>.075</td>
<td>4.26 (2.28)</td>
<td>$F_{\text{Course}}$ (1,43)</td>
</tr>
<tr>
<td>Course 2 – didactic vs.</td>
<td>4.75 (2.17)</td>
<td>$F_{\text{Pre}}$ (1,45)</td>
<td>18.47</td>
<td>.000</td>
<td>.291</td>
<td>4.75 (2.17)</td>
<td>$F_{\text{Pre}}$ (1,45)</td>
</tr>
<tr>
<td>Course 3 – mixed</td>
<td>4.60 (2.01)</td>
<td>$F_{\text{Course}}$ (1,45)</td>
<td>0.16</td>
<td>.694</td>
<td>.003</td>
<td>4.26 (2.28)</td>
<td>$F_{\text{Course}}$ (1,45)</td>
</tr>
</tbody>
</table>

Note: Covariate = score at pretest; alpha adjusted to .05/6 = .0083; bolded $p$ values are significant.
Discussion

The SysThema study has been investigating the means by which teacher education can improve student teachers’ PCK for teaching systems thinking. Systems thinking skills are important in helping younger people understand the complexity of relationships when following current sustainable development trends throughout the world. Learning about complex systems, however, is challenging and requires special teaching delivered by well-trained teachers. To investigate the preparedness in teaching systems thinking in school, we designed three different types of intervention courses for student teachers in Biology and Geography. One course focused on promoting mainly subject matter knowledge for teaching systems thinking, as it is common in academic track teacher education. Another course focused on promoting pedagogical and didactical knowledge, because these methods are common in the non-academic track teacher education. The third course mixed these contents in equal parts. This design is unique in science teacher education. We found no studies (Großschedl et al., 2014; Jüttner & Neuhaus, 2012; Mahler et al., 2017; Schmelzing et al., 2013) that investigated quantitatively the development of student teachers’ PCK during teacher education at the university level in a sample of more than 100 participants, although teacher education seems to play a particularly important role in the development of PCK (Kleickmann et al., 2013).

When developing the questionnaire, we were faced with many challenges. First, we needed a multiple measure, qualitative questionnaire that assesses intervention effects and the results of which could be coded for quantitative analysis. In previous research, only qualitative analyses were conducted from surveys or the methods had not explored intervention effects (cf. Großschedl et al., 2014; Jüttner & Neuhaus, 2012; Schmelzing et al., 2013). Thus, we entered a nearly unexplored area of research. The reliability of the questionnaire was particularly challenging. We dismissed the pretest low reliability, because student teachers do not possess an extensive amount of knowledge of teaching systems thinking. The reliability increased in the posttest after the intervention and was verified by a retest reliability with the follow-up test. Given that the reliability of each facet was not satisfied, only the overall findings in student teachers’ PCK were reported. For reasons of the content validity, we adhered to the conceptualisation despite the limited informative value of Knowledge of students’ understandings in systems thinking.

Regarding the main research question, the results showed that student teachers’ PCK for teaching systems thinking can be developed in teacher education. This result is consistent with qualitative studies proposing that teachers’ PCK can be improved (Brovelli, Bölstleri, Rehm, & Wilhelm, 2014; Rozenszajn & Yarden, 2014). The results of the pretest measurement before the intervention is consistent with the assumption that student teachers’ PCK for teaching systems thinking exists only in a marginal framework when student teachers begin their studies. The strength of the effect after the intervention shows that student teachers’ PCK for teaching systems thinking can be extended effectively during courses in teacher education. It should be noted, however, that a learning effect is likely to have occurred just by working on the questionnaire, which can explain the increasing improvement of the control group in the second measurement. This observation does not dismiss the success of our intervention. In further analyses, the results showed significant differences between each of the intervention groups and the control group in addition to the high effect sizes.
We also found that the effectiveness of the different treatment courses was possible to statistically demonstrate. Researchers argue very differently for a certain quantity of a technical or a more didactic teacher education (Ball et al., 2005; Borko & Putnam, 1996; Krauss et al., 2008; Kunter & Baumert, 2013). The findings in our study suggest that pedagogical and didactical teacher education courses with mainly PCK topics achieve significantly higher effects than courses with mainly technical topics in teaching systems thinking, which is common in German academic track teacher education (Gymnasium). The results of the didactical course, however, were not significantly different from the results of the mixed course. Hence, only tentative conclusions can be drawn from our results for future teacher education in science teaching.

If the goal is to promote student teachers’ PCK for teaching systems thinking, a course with mainly didactical content and an intervention with a mix of technical and didactical content seems to be appropriate. The second conclusion to be drawn from our findings is that a mainly technically orientated course without any pedagogical and didactical aspects seems to be less effective in fostering student teachers’ PCK for teaching systems thinking. These findings are consistent with the findings of Mahler et al. (2017) that merely addressing CK insufficiently supports students in the acquisition of systems thinking abilities in biology. This shortcoming needs to be addressed by educators, because academic track teachers in Germany (Gymnasium), who will presumably be qualified in the sciences they teach and will join mainly the same courses as future biologists or geographers, will have trained without any content that develops their PCK. Given the importance of developing teachers’ PCK as is the claim in current teacher education (Abell, 2007; Ball et al., 2005; Kunter & Baumert, 2013; Shulman, 1986, 1987; Tamir, 1988) and the consistent positive relationship between PCK and students’ performance (Baumert et al., 2009; Fennema et al., 1996; Kunter et al., 2013; Mahler et al., 2017) teacher education needs to be adaptive in changing their curriculum by providing additional didactic content.

Nonetheless, the study had several limitations and caution should be taken that the findings are not over-generalised. The sample size in each experimental group was relatively small (n < 30) and the inability to assign randomly the student teachers to experimental courses can be improved in future experimental designs. Another limitation is the collection and analysis of the qualitative data. Student teachers’ PCK was determined by their responses on a questionnaire. A questionnaire designed for collecting qualitative data and then transformed to quantitative data bears many uncertainties that could interfere with the findings and conclusions of reliable qualitative analysis.

We hope that the empirical findings provided by our study will stimulate reflection and discussion in the improvement of future teacher education. Given the limited generalisability of our findings, a challenge for future research on science teacher education will be to examine the effects of courses with different technical and didactical input.

**Disclosure statement**

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References


