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Effects of Teachers' Professional Knowledge and Their Use of Three-Dimensional Physical Models in Biology Lessons on Students' Achievement

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Abstract: Using three-dimensional physical models elaborately in their learning, students can develop high-level understanding of models and modeling in science, thereby attaining higher achievement. However, there are in the literature few indications of how teachers should use three-dimensional physical models in instruction and whether teachers' professional knowledge is a prerequisite for teaching with elaborate use of models. Therefore, our study used a mixed-methods approach to analyze the effects of biology teachers' domain-specific pedagogical content knowledge (PCK) and content knowledge (CK) on students' achievement mediated by elaborate model use (ELMO). Our quantitative sample comprised 36 German secondary school teachers whose lessons on the topic of neurobiology were videotaped twice (N = 72 lessons). Teachers completed professional knowledge tests on their PCK and CK. Students' achievement was measured using pre- and post-knowledge tests. Our qualitative analysis involved five selected teachers according to aspects of ELMO. The results of our study indicated that teachers' PCK and CK had no direct effect on students' achievement. However, teachers' PCK had a significant indirect and positive effect on students' achievement mediated by ELMO. The findings of our study can provide teachers and researchers examples of how to implement biology instruction with elaborate use of three-dimensional physical models.

Keywords: three-dimensional physical models; pedagogical content knowledge; students' achievement; mixed-methods approach; explanatory sequential design; video study; biology education; biology practice

1. Introduction

As a result of international comparative studies, educational reforms in several countries have focused on developing and implementing National Education Standards (NES) in science education [1–3]. To state these NES more precisely, several dimensions were formulated. In Germany, four dimensions were established by the Conference of the Ministers of Education (KMK): content knowledge, scientific inquiry, communication, and scientific judgment [4]. More specifically, content knowledge represents a subdimension of a subject-specific content-related dimension and the other three dimensions are actually subdimensions of a process-related dimension [4]. A process-related dimension takes into account several constructs of scientific inquiry and scientific reasoning [2,5–9] and has become increasingly important. Within this process-related dimension of NES, scientific methods and the use of models in instruction were included as part of the learning in scientific inquiry; [2]. In this regard, models and modeling play a central role in science instruction and science education [10,11]. Additionally, science instruction should foster students' understanding of models and modeling in science [1–3]. Therefore, models can be seen as "representations of objects, phenomena, processes, ideas and/or their system" [12] (p. 7). Models are a representation of real and mental objects [13]. In contrast to representations, models are also used to generate information about the real objects [13]. They can be used for testing ideas and drawing conclusions on the original object. They can be seen as important research tools in science and sciences instruction and have an interpretative nature [14]. Therefore, models in contrast to representations can be manipulated and explain the original through examination [15] However, activities for students or teachers to use models in classroom are hardly present [16]. Several studies already showed that using models in instruction has a more significant effect on students' achievement, compared to other teaching materials, for example [17–20]. However, aspects of (1) which way models should be used in biology instruction to achieve higher students' achievement in biology, and (2) which dimensions of professional knowledge do teachers need for using models in leading to an increase in students' knowledge in biology, have remained unclear.

Therefore, this mixed-methods study with an explanatory sequential design, [21], first analyzed the effects of subject-specific knowledge dimensions, and different characteristics of the model use in biology instruction on students' achievement. Additionally, in order to describe in more detail the use of models, which fosters students' achievement in biology, contrasting extreme cases of teachers were used in the qualitative phase of the study. In the following sections, we review the previous studies concerning the use of models in science instruction, the effects of teachers' pedagogical content knowledge (PCK) and content knowledge (CK) on model use, as well as the effects of using models on students' achievement.

1.1. The Nature and Purpose of Models in Science Instruction

The aim of science education is to foster students' learning of science, learning about science, and learning to do science [22]. Harrison and Treagust [23] assumed that students learn and understand science in an elaborate way as they learn and understand models created by scientists. Therefore, using models in instruction is one important teaching strategy in science; [24]. Nevertheless, there is still no general point of view of how 'models' can be defined [25]. According to a simple definition, models are "representations of objects, phenomena, processes, ideas and/or their system" [12] (p. 7). In instruction, teachers use models to make dangerous and complex scientific phenomena accessible for students and to illustrate certain aspects of a content area [13,26,27]. While introducing NES in science, for example, in Germany [2], and in the U.S. [3], the demand for using models as tools for scientific inquiry, for example, for predicting scientific phenomena, becomes even more important (e.g., [9,28–33]). Through models, complex phenomena are illustrated for students in an understandable way [14,34]. Therefore, models can support the development of mental representations and conceptual ideas of the phenomenon [35]. Additionally, modeling illustrates the work of researchers in science and scientific inquiry for students. Both aspects foster the development of students' scientific literacy as a main goal of scientific instruction. However, such implementation of instruction using models is hardly represented in science classrooms [9,16,36–38]. Additionally, Gogolin and Krüger found that "[s] tudents' levels of understanding of the nature and the purpose of models increase only little across grades" [39] (p. 1).

1.2. Teachers' Domain-Specific Professional Knowledge Including Knowledge about Models and Modeling in Science

The use of models is one of the biology-specific teaching strategies. Therefore, the knowledge about models and modeling can be described as an important facet of teachers' pedagogical content knowledge (PCK); [24,40–42]. PCK is part of teachers' domain-specific knowledge besides content knowledge (CK) [24,41]. CK includes knowledge about subject-specific content and the conceptual understanding of this content; [41]. In contrast, PCK mainly consists of knowledge about students' misconceptions as well as knowledge about teaching strategies and representations, for example [41,43]. Theoretically, teachers with high PCK are able to make content understandable for students [44].

Teachers' PCK of models and modeling consists of several further parts. Schwarz [30] described three aspects, which can be taken into account in this context: 'Knowledge of science', 'knowledge of science learners' and 'views of effective science teaching'. A high knowledge of science is expressed in the understanding of models as a generative tool, which can be revised, and their importance in inquiry and application [45,46]. Knowledge of science learners describes the knowledge of teachers about students' prerequisites, which they need, when they learn aspects of scientific reasoning by models [46]. Views of effective science teaching include the use of models for scientific inquiry. Therefore, individual concepts of the learning content will be illustrated by multiple perspectives [46]. On the basis of these three aspects of teachers' PCK about models and modeling, it becomes clear that teaching with models has to be in line with the demands of National Education Standards [2]: fostering students' understanding of science through elaborate use of models in instruction. Elaborate use of models in instruction is characterized by using models as tools of scientific reasoning, formulating scientific research questions and hypotheses, revising models based on empirical data, and reflecting on them critically [47]. Therefore, a "teacher's knowledge and views will significantly impact her instructional planning and assessment practices using models" [46] (p. 4). It seems obvious that teachers' PCK is important for effective implementation of models in instruction to foster students' achievement. In order to use models in a way that helps students to develop elaborate understanding of models and modeling in science, science teachers need understanding of as well as knowledge about models and modeling [48,49].

Several studies already have focused on describing knowledge about models and modeling of preservice and in-service teachers [16,25,37,38,46,48,50] or developed professional development programs on this topic [49–55]. These studies described the knowledge structure of preservice or in-service teachers and possibilities to improve their limited and inadequate knowledge about models and modeling. First of all, it seems reasonable to identify effects of teachers' knowledge dimensions on their use of models in instruction and to analyze effects of different facets of PCK and CK afterwards. However, effects of different dimensions of teachers' knowledge on model use in instruction were seldom considered. Before our study, some studies which described and fostered teachers' knowledge about models and modeling as part of their PCK were conducted (e.g., [35,46]). However, comparison of different knowledge dimensions and their individual effects on using models in instruction was hardly taken into account.

1.3. Effects of Using Models in Instruction on Students' Outcome

As students develop an elaborate understanding of models and modeling in science through using models elaborately in their learning [15,56], elaborate model use should positively affect their learning outcomes in biology. Several intervention studies provided the first indications of the effect of model use on students' learning (e.g., [17–20,35,56]). Students working with models showed higher abilities in answering knowledge-transferring tasks and generated a more elaborate understanding of models and modeling in science [34]. Additionally, students learned new concepts more easily (e.g., [56]). Furthermore, students who worked with models learned more accurately and appropriately than did other students without using models (e.g., [17–20]). The study of Barak and Hussein-Farraj [17] additionally indicated that students developed higher level thinking when they worked with models on their own during instruction. Barak and Hussein-Farraj [17] defined higher level thinking as the students' ability to transfer between several representations with various dimensions. Several aspects of model use in instruction, which is effective for fostering students' achievement, were derived from empirical studies and theoretical assumptions and were summarized in the construct elaborate model use (ELMO) of [47,57]. ELMO comprises (1) a characterization of the used models, e.g., which level of complexity the model has; (2) the way the model can be integrated into instruction, e.g., how the model is introduced to students; and (3) the way the model is used to foster scientific reasoning with focusing demands of German NES, e.g., if and how the model was critically reflected during the model use (detailed description of conceptualization of ELMO see 47 and 2.2.2). Aspects of ELMO can be used for describing model use in videos as well as live observations and measured quantitatively using a coding scheme [47,57].

Previous studies only investigated teachers' knowledge about models and modeling, and the effects of using a model on students' achievement. There were hardly any studies that combined these three aspects: teachers' professional knowledge, instructional quality features, and students' achievement [58]. In particular, there were no studies on facets of PCK including the use of models, one of the teaching strategies of science (for an overview, see [59]). So far, results of several studies have not shown any effect of PCK on several instructional quality features as well as on students' learning (e.g., [60,61]). Using models in instruction as one of these instructional quality features is not taken into account for science teachers' PCK.

1.4. Research Questions and Hypotheses

One main goal this study was to identify which subject-specific dimension of teachers' knowledge (PCK or CK) leads to elaborate model use and, therefore, higher students' achievement. Previous studies indicated that teachers' knowledge about models and modeling in science is limited and divergent (e.g., [16,25,37,38,48,50]). As teachers' knowledge greatly influences instruction and assessment practice [46], the effects of teachers' different knowledge dimensions on teaching practice should be analyzed. Additionally, we hardly know what effective use of models in instruction looks like as previous studies only compared using models with other teaching materials and identified effects on students' learning [17–20,35,56].

Addressing these research gaps, we conducted a mixed-methods study with an explanatory sequential design [21]. In the quantitative phase of our study, we analyzed the effects of teachers' PCK and CK on students' achievement mediated by their specific model use. In our study, this specific model use is represented by ELMO. An elaborate understanding of models provided by this way of teaching may facilitate students' learning of content [54], thereby leading them to higher achievement. Therefore, our research questions were:

RQ1: In which way should models be used in biology instruction to achieve higher students' achievement in biology?

RQ2: Which dimensions of professional knowledge do teachers need for using models in a way leading to an increase in students' knowledge in biology?

Based on our research questions and theoretical aspects, we formulated the following hypotheses for the quantitative phase of our study:

Hypothesis 1 (H1). *PCK and CK do not have a direct effect on students' achievement.*

Hypothesis 2 (H2). *PCK has an indirect effect on students' achievement mediated by elaborate model use; CK does not show an indirect effect.*

Teachers' professional knowledge was measured using paper-pencil tests. Their instruction was measured by videotaping biology lessons, which were analyzed through a theoretically devised coding scheme focusing on ELMO.

Additionally, we were interested in a qualitative description of the application of ELMO in biology instruction. Therefore, we formulated an additional research question:

RQ3: How can an effective model use in biology instruction be described?

Therefore, in the qualitative phase of our study, we described elaborate model use in biology instruction by comparing the extreme cases encountered by teachers. With these results, elaborate model use with examples can be understood in a better way by researchers, preservice and in-service biology teachers. In choosing a mix-methods approach, our assumption was "that the uses of both quantitative and qualitative methods, in combination, provide a better understanding of the research problem and question than either method by itself" [21] (p. 535).

2. Materials and Methods

2.1. Design and Sample

This study was embedded in the project Professional Knowledge of Teachers in Science (ProwiN), which is a cooperative project between different German universities [24]. In this project, the effects of different dimensions of science teachers' professional knowledge on different features of instructional quality, and students' outcomes are analyzed and the findings of the subjects biology, physics, and chemistry were compared [24]. In the biological part of the project, 43 teachers participated and two lessons of each teacher on the topic neurobiology were videotaped (N = 85 lessons) [62]; for one teacher, only one lesson could be videotaped owing to illness. All participating teachers taught the subject biology and another a science subject. In the videotaped lessons in our study, teachers taught the topic neurobiology as described in the Bavarian curriculum for the subject biology [63]. This study analyzed a subsample of 36 teachers (51% female; teaching experience after the traineeship in years: M = 6.3, SD = 5.8; age in years: M = 35.9, SD = 8.5) from the biological part of the ProwiN project and their 72 lessons (length of the lessons in minutes: M = 43.4; SD = 8.5) [47,62]. The participating teachers were given no requirements on how they have to teach or how they have to use three-dimensional models in their classroom instruction. This subsample was used, because we could not collect students' post-test achievement data of four teachers and three teachers did not use models during the videotaped instruction. Therefore, the student subsample consisted of 736 students in grade 9 (age: M = 14 years, SD = 0.61).

A mixed-methods approach using an explanatory sequential design was used in order to address the aims of the study [21] (pp. 540–543). This research design consisted of two phases of data collection and analysis: quantitative and qualitative phases (see Figure 1).

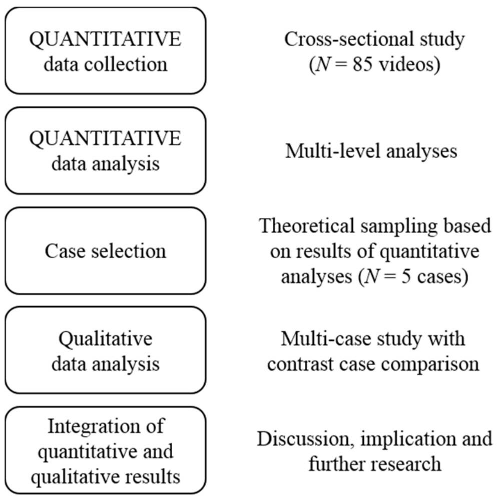

Figure 1. Overview of mixed-methods sequential explanatory design conducted in this study.

The priority of the study was given to the quantitative phase and qualitative data was used to complement the quantitative results. In the quantitative phase, multi-level-analyses with a large sample were conducted. For the qualitative case analysis, a subsample of the data from the quantitative phase was selected. Therefore, both quantitative and qualitative methods were connected [64].

2.2. Quantitative Phase

Within the quantitative phase, a cross-sectional study was conducted. To test our two hypotheses, teachers' domain-specific knowledge dimensions PCK and CK and students' achievement were collected in a pre-post design. Additionally, elaborate model use of the videotaped lessons was analyzed according to a theoretically devised category system [47].

2.2.1. Domain-Specific Knowledge Dimensions PCK and CK

The domain-specific knowledge dimensions PCK and CK of the participating teachers were measured using a shortened version of the paper-and-pencil knowledge test of [65] before videotaping teachers' lessons. The PCK part of the test included eight open-ended items and one multiple-choice item on the knowledge about biology-specific instructional strategies—using models or experiments—and knowledge about students' misconceptions on the topic neurobiology. The CK part of the test (12 items) included open-ended and multiple-choice items on neurobiology and cytology. The validity of both knowledge tests was determined by contrast-groups comparisons [66] and think-aloud interviews [67]. In contrast-group comparisons between biology secondary school teachers, certified biologists and certified pedagogues, it was found that the biology secondary school teachers performed significantly higher in the developed PCK test than did both the certified biologists and certified pedagogues [67]. Additionally, a high content validity for the PCK items was examined by think-aloud interviews with German and American biology teachers [66]. For the CK test, [66] showed that the biology secondary school teachers obtained higher scores than did the certified pedagogues. Both measurements indicated good validity of both PCK and CK test. To verify the objectivity of the tests, 10% of the open-ended items of the PCK and CK test were coded by a second independent test marker and the *ICC* (Intraclass Correlation Coefficient) measures were found to be very good for PCK items: $ICC_{(unjust)} = 0.96$; $F\ (116,116) = 24.30$, $p < 0.001$; and for CK items: $ICC_{(unjust)} = 0.94$; $F\ (119,119) = 16.63$, $p < 0.001$ [62]. A Rasch analysis for both knowledge tests was conducted separately using the partial credit Rasch model (PCM) [68] (see Supplementary Material). Rasch analysis with PCM gives the possibility to verify the reliability of a used test instrument [69,70]. Therefore, values of item reliability and person reliability of our tests were checked. However, these Rasch values are not comparable with Cronbach's alpha values [70]. The results of Rasch analysis—using item reliabilities (0.96 for PCK items; 0.99 for CK items), and person reliabilities (0.53 for PCK items; 0.73 for CK items), as well as Infit-/Outfit-MNSQ (mean-square; all values less or equal to 1.5)—showed satisfactory values [62,70]. The low person reliability was a result of a relatively small sample size for Rasch analysis [68,70]. However, as the item reliability of the PCK test showed a high value, these values still indicated a reliable measurement of PCK [70]. The resulting measures from Rasch analyses were used for further analyses.

2.2.2. Instructional Quality Feature Elaborate Model Use (ELMO)

In our analysis of ELMO, only the use of three-dimensional physical models was taken into consideration because our PCK test only included items on this type of models. Three-dimensional physical models comprise structural models and functional models, which can be touched by students or teachers. In our study, this definition of model did not include illustrations, schematic drawings or computer simulations. Additionally, German NES only describe models in terms of three-dimensional physical models [2]. Diagrams, which can be seen as two-dimensional physical models, are not included in the dimension scientific inquiry in German NES [2]. Therefore, diagrams were excluded from our analysis. To analyze model use in instruction, a theoretically devised event-based category system was developed [47]. The category system comprises three aspects (1) characteristics of the model; (2) the way the model is integrated into instruction; and (3) the way the model is used to foster scientific reasoning for operationalizing elaborate model use (ELMO) in biology instruction [47] (see Table 1). Examples of the different categories are shown in the qualitative results (see Sections 3.2.3–3.2.5.

Table 1. Overview of three aspects of elaborate model use (ELMO) and their categories (adapted from [47]).

Aspect of Elaborate Model Use	Category in Category System	Gradation of the Category
Characteristics of the model	Level of abstraction	Low, middle, or high abstraction compared with real objects
	Level of complexity	Showing facts, relations, or concept
	Fitting to the learning goal	No fitting or fitting of level of abstraction and level of complexity to the learning goal
The way the model is integrated into instruction	Purpose of the model	Illustration or tool for scientific reasoning
	Introduction of the model	No, short or detailed introduction of the model
	Students working with the model	Teachers vs. students with teacher working with models
The way the model is used to foster scientific reasoning	Predict scientific phenomena (scientific inquiry)	No formulation vs. formulation of scientific research questions or hypothesis
	Revise models (scientific inquiry)	No regard or regard to scientific research questions or hypothesis
	Critical reflection	No critical reflectionf, incidentally critical reflection naming one aspect, incidentally critical reflection naming more than one fact, detailed critical reflection naming one fact or detailed critical reflection naming more than one fact

These three aspects and their different categories summarize theoretical assumptions and empirical findings, which seem to foster students' knowledge. Therefore, the construct ELMO should show a possibility of how teachers can work effectively with models in instruction. The aspect characteristics of the model refers to the nature of the used model [47]. Therefore, the level of abstraction [15,71,72], the level of complexity [73,74], and their fitting to the learning goal were assessed. In the way how the model is integrated into instruction, different categories of 'good' biology instruction and modeling practices were taken into account [47]. Classroom situations, in which teachers used models, were analyzed according to (1) introduction of the model [75], (2) purpose of the model—illustration or teaching tool for scientific inquiry [9,16,36–38]—and (3) students working actively with the model [15]. The aspect the way the model is used to foster scientific reasoning included demands of the German NES [1–3]; and therefore, different categories of scientific inquiry, for example, predictive characteristic of models and the critical reflection were taken into account (e.g., [30–33,47,76]).

The videotaped lessons were analyzed according to the developed category system using the program Videograph [77]. Therefore, we identified phases of teaching containing the use of models. Then, we conducted an in-depth analysis on these identified phases using the individual categories of the category system.

For objectivity analysis, a second independent coder coded 10% of the videos and the coding showed a good inter-rater agreement with values of Cohen's kappa between 0.79 and 1.00 [47]. The different categories of each aspect were analyzed using the PCM [68] (see Supplementary Material). The fit values of Rasch analysis were satisfactory [47]. One ELMO mean score for each teacher was calculated and used for further analyses. Further information on video data was reported in Author [47].

2.2.3. Students' Data

Students' achievement was measured before and after videotaping using a paper-and-pencil knowledge test [62]. The pretest are used to measure students' prior knowledge on the topic neurobiology with a focus on reflex arc and as one control variable on the student level in further calculations. The pretest and post-test did not only contain different tasks on factual knowledge of the topic neurobiology, but included tasks on conceptual knowledge and tasks on scientific reasoning (18 tasks in pretest; 22 tasks in post-test). Factual knowledge tasks included questions on specific definitions, terminology or details in biology [78]. In contrast, conceptual tasks were characterized by formulating relations between single facts [78]. For solving such tasks, students have to have a higher conceptual understanding of the content [79]. Additionally, students have to "[engage] in practices to make sense of content and recognize how a scientific body of knowledge is developed" [80] (p. 663). Therefore, these tasks can be described as high-level tasks, which require higher level and complex thinking in contrast to algorithmic thinking in the tasks on factual knowledge [80,81]. Students need a high understanding of science concepts as well as a certain level of self-regulation of their cognitive processes in order to solve these conceptual tasks [81]. Examples for factual and conceptual tasks are shown in Table 2.

Table 2. Examples for different types of tasks in students pretest and post-test, sample solution and literature [47,62].

	Example of an Item	Sample Solution	Literature
Factual knowledge	Note a mnemonic sentence that describes all the important characteristics of a reflex.	A reflex is a congenital protective function without processing in cerebrum, follows according to a fixed scheme and can be rare deliberately influenced.	Factual knowledge tasks including questions on specific definitions, terminology or details in biology [79]
Conceptual knowledge	Explain how the human nervous system is adapted to humans' way of living. Give two examples.	e.g., centralization of the human nerve system for more complex movements.	Conceptual tasks were characterized by formulating relations between single facts [79]—core ideas of NES in Germany [2]
Scientific reasoning	In the figure below, you can see an experiment about hearing. Please make one hypothesis on what will be tested in this experiment.	This experiment tests if and under which preconditions a human has directional hearing.	Generating hypothesis as part of the dimension "scientific inquiry" of NES [2,7]

Both tests included open-partial-credit and multiple-choice items. However, neither the pretest nor the post-test contained tasks about models in neurobiology.

To verify the objectivity of our test instruments, a second independent test marker coded 10% of the open-partial-credit items. The coding showed high agreement in both the pretest: $ICC_{(unjust)} = 0.99$, $F\,(1277{,}1277) = 77.92$, $p < 0.001$, $N = 1278$; and the post-test: $ICC_{(unjust)} = 0.98$, $F\,(2477{,}2477) = 56.50$, $p < 0.001$, $N = 2478$ [62]. The pretest and post-test were analyzed using the PCM [68] (see Supplementary Material). The reliability of our content knowledge tests were verified by the Rasch analysis. Therefore, the item and person reliability were of both tests were checked by the statistical thresholds values according to Boone et al. [70]. Item reliabilities (1.0 for both tests), person reliabilities (0.63 for pretest; 0.78 for post-test), and Infit-/Outfit-MNSQ (all values were less than 1.3) all showed satisfactory values [62,70].

Students additionally completed a four-point Likert-scale questionnaire (from 1 = strongly disagree to 4 = strongly agree) on motivational aspects including the scale willingness to make an effort

(3 items; Cronbach's alpha was 0.72) based on Wild, Gerber, Exeler, and Remy [82]. Willingness to make an effort represents the readiness of students to concern themselves independently with the lesson content. One of the items used was: "When I will be examined in biology lessons (e.g., oral examination), I make a big effort to be successful." This questionnaire scale was used as an additional control variable for explaining the variance on the student level.

2.2.4. Quantitative Data Analysis: Multilevel Path Analyses

We measured teachers' PCK and CK, as well as their ELMO on the class level, whereas we measured students' content knowledge in the pretest and posttest and their willingness to make an effort in the questionnaire on the student level. Therefore, our data have a hierarchical structure with two levels. The outcome variable students' content knowledge in post-test was analyzed on both levels. Because of the data's hierarchical structure, we used the multilevel model program Mplus 7.3 [83], where class- and student-level data were modeled simultaneously. For all multilevel path models, the maximum likelihood estimator was used and standardized values were shown. For evaluating the models' quality, we used fit values—comparative fit index (CFI > 0.90), root-mean-square error of approximation (RMSEA < 0.05), and standardized root-mean-square residual (SRMR < 0.08), separated for the between-and within-class covariance matrices ($SRMR_{between}$, $SRMS_{within}$)—and compared them with values of good fit according to Hu and Bentler [84]. Initially, a null model was calculated to identify the variance, which can be explained at the class level.

For analyzing the single mediation—and therefore our two hypotheses—we performed calculations based on the methods in the literature [85–87]. Significant total effects, however, are not a prerequisite for mediation analyses [87]. The calculations of the null model showed the possible variance on the class level, which we can be explained with our analyzed variables. First, we analyzed the total effects of teachers' PCK and CK with multilevel path models (M1a, M1b, and M1c) on students' content knowledge in the post-test (see A in Figure 2). Second, we calculated a multilevel path model (M2), in which we analyzed the effects of the two domain-specific dimensions of teachers' professional competence (PCK and CK) on their ELMO, which in turn affected students' content knowledge in the posttest. In Model M2, the direct effect (see path c′ of B in Figure 2) and indirect effect of PCK (see path ^{a}PCK and b of B in Figure 2) and CK (see path ^{a}CK and b of B in Figure 2)—through the mediation by their ELMO—on students' content knowledge in the post-test are calculated.

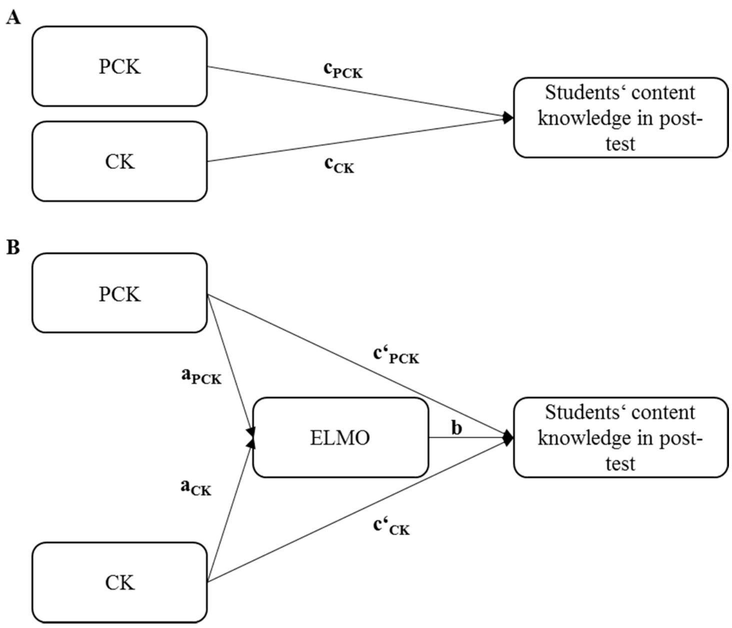

Figure 2. Mediation model of the quantitative analysis.

For all the calculations, we controlled for students' achievement in the pretest and students' willingness to make an effort at the student level; and, therefore, we assumed that the differences in students' achievement can be attributed to variables at the class level.

2.3. Qualitative Phase

Qualitative analysis was conducted to get a deeper understanding of the theoretically devised construct ELMO. Additionally, examples for implementing several categories of ELMO in the classroom were shown. Through the qualitative analysis, differences in teaching were clarified when teachers worked with models elaborately.

2.3.1. Qualitative Research Design

For the qualitative phase, we used a multiple-case-study design with comparative cases of teachers to analyze the data [88–90]. Such a study design helps to understand a specific idea and abstract principles in detail [90]. Multiple cases help to describe, explain and illustrate these ideas and principles [90,91]. Furthermore, case studies are suitable for qualitative methods in mixed methods research [88].

2.3.2. Case Selection

We selected our cases of teachers using a theoretical sampling method [92]. At the start of our analysis, the total number of cases had not been defined. During the analysis, more cases were included to understand the description of the construct ELMO and its categories in a better way. Additionally, cases were selected with contrasting patterns based on the results of the quantitative analysis. Therefore, we plotted the mean score of PCK against the mean score of ELMO for each teacher. To choose extreme cases, only cases of the upper right quadrant and the lower left quadrant of the scatter plot were considered.

Finally, five cases of teachers were selected for the comparative qualitative analysis. Details about the results of this analysis are presented in the following section.

2.3.3. Qualitative Data Analysis

All the videotaped lessons of participating teachers were transcribed. The qualitative data analysis was conducted using the qualitative research methods [21,88–90]. The identified phases of model use in our quantitative analysis provided the basis for our qualitative analysis. In the first step, all cases were analyzed within itself. By reading through the transcript of each case, several memos were written [93]. In qualitative analysis, several patterns were identified and summarized into general categories. Therefore, we devised and then used our theoretically category system of ELMO with the three aspects or variables—(1) characteristics of the model, (2) the way how the model is integrated into instruction, and (3) the way the model is used to foster scientific reasoning—in our quantitative analyses. In the next step, different sections of each case were coded for each variable and a cross-case thematic analysis was conducted. The different extreme cases and how the teachers implemented each variable in their model use were compared and the differences between the cases were recorded in detail. For explaining the differences of several variables of our category system between these extreme cases, further cases were added to our analysis during the coding process (see case selection).

Two of the cases were coded by a second independent coder to verify the objectivity of our qualitative analysis. Discrepancies were discussed between both coders until reaching agreement for the final description of the coding. The selected teachers and all the variables of ELMO, for example, expected level of abstraction and level of complexity, were shown as contrasting cases in the results. The level of abstraction and level of complexity variables were only described exemplarily for a better understanding of both.

3. Results

3.1. Quantitative Results

In the first step, we analyzed the intercorrelations between all the variables of model use at the student and class levels including their means and standard deviations. Table 3 shows the latent correlations between all the variables used for multilevel analyses. By these correlations, insights regarding our hypotheses can be provided. The instructional quality feature ELMO showed only a small significant correlation with teachers' PCK. Students' achievement in the post-test also correlated positively with instruction with high significance. Additionally, students' achievement in the pretest (a latent variable for students' prior knowledge) had a highly significant positive correlation with students' achievement in the posttest. Willingness to make an effort showed positive small or moderate correlations with students' achievement in the pretest as well as in the post-test. These results provide only the first indication of possible effects in further multilevel path models.

Table 3. Means, standard deviations, and intercorrelations for variables on class level and student level.

Variable	*M*	*SD*	1	2	3	4	5	6
Class level								
Teacher variable								
1. Pedagogical content knowledge (PCK) [a]	−0.34	0.52	-					
2. Content knowledge (CK) [a]	0.93	0.47	0.14	-				
Instructional variable								
3. ELMO [a]	1.12	1.27	0.35 *	−0.04	-			
Student level								
4. Student achievement in posttest [a]	0.04	0.48	0.06	−0.09 **	0.13 ***	-		
5. Student achievement in pretest [a]	−0.44	0.61	−0.12 ***	−0.05	−0.17 ***	0.32 ***	-	
6. *Willingness to make an effort* [b]	3.4	0.57	0.04	−0.02	0.03	0.24 ***	0.11 **	-

Note: The presented intercorrelations are correlations (r) between values used for further calculations. [a] Measures of Rasch analyses. [b] Questionnaire with a four-point Likert-scale. * $p < 0.05$.** $p < 0.01$. *** $p < 0.001$.

The null model showed that 19.6% of the variance in students' achievement in the post-test could be explained by the variables on the class level (e.g., teacher or instructional variables).

Then, we analyzed the total effects of the subject-specific dimensions of teachers' professional knowledge on students' achievement in the post-test using multilevel path models. In all the models, we controlled for students' achievement in the pretest and willingness to make an effort on the student level. In models 1a and 1b (see Table 4), we separately analyzed the total effects of PCK and CK on students' achievement in the posttest. For both models, the calculated fit values were good—Model 1a: $\chi^2(3) = 130.59$, $p < 0.001$; $CFI = 1.000$, $RMSEA = 0.000$, $SRMR_{within} < 0.001$, $SRMR_{between} < 0.001$; Model 1b: $\chi^2(3) = 130.53$, $p < 0.001$; $CFI = 1.000$, $RMSEA < 0.001$, $SRMR_{within} < 0.001$, $SRMR_{between} < 0.001$. In Model 1c, PCK and CK of the teachers did not simultaneously predict students' achievement in the posttest—fit values: $\chi^2(4) = 132.28$, $p < 0.001$; $CFI = 1.000$, $RMSEA < 0.001$, $SRMR_{within} < 0.001$, $SRMR_{between} < 0.001$. Teachers' PCK and CK did not have a total effect on students' achievement neither in the separate models (Models 1a and 1b) nor in the simultaneous model (Model 1c).

Table 4. Predicting achievement in posttest by teachers' PCK and CK.

Model [a]	Achievement in Posttest	
	β	SE
1a		
PCK	0.20	0.17
1b		
CK	−0.20	0.17
1c		
PCK	0.23	0.17
CK	−0.23	0.17

Note: [a] The regression models included achievement in the pretest and willingness to make an effort at the student level as control variables.

In the next step, we used a two-level mediation path model, where instructional quality by ELMO mediated the effect of teachers' domain-specific knowledge on students' achievement in the post-test. Again, we controlled for students' achievement in the pretest and willingness to make an effort on the student level. Model M2 showed a good fit: $\chi^2(2) = 1.52$, $p = 0.468$; $CFI = 1.000$, $RMSEA < 0.001$, $SRMR_{\text{within}} < 0.001$, $SRMR_{\text{between}} = 0.054$. The results are shown in Table 5.

Table 5. Predicting achievement in post-test by teachers' domain-specific knowledge and ELMO.

	Mediator Variable		Dependent Variable	
	ELMO		Achievement in Posttest	
	β	*SE*	β	*SE*
Class level				
Teacher variables				
PCK	0.36 *	0.15	0.10	0.18
CK	−0.09	0.16	−0.19	0.16
Instructional variable				
ELMO			0.38 *	0.17
R^2	0.13		0.17	
Student level				
Achievement in pretest			0.38 ***	0.03
Willingness to make an effort			0.19 ***	0.03
R^2			0.19	

* $p < 0.05$. *** $p < 0.001$.

As shown in Table 3, there was no significant correlation between PCK and CK ($r = 0.14$; $p = 0.39$). Both PCK and CK did not show a direct effect on students' achievement in the post-test. PCK effects positively ELMO in instruction and explained 13% of variance on the class level. Furthermore, ELMO showed a positive significant effect on students' achievement in the post-test and explained 17% of its variance on the class level. Additionally, the total effects of PCK on students' achievement in the post-test were larger than the direct effect. Therefore, it can be concluded that ELMO had a positive significant effect on students' achievement in the post-test and was, itself, positively and significantly effected by teachers' PCK, but not by their CK.

The two control variables on the student level had a significant positive effect on students' achievement in the posttest and together explained 19% of its variance on the student level.

3.2. Qualitative Results

3.2.1. Teachers

Figure 3 shows the scatter plot with the selected case teachers for the qualitative analysis. Tom (all teachers' names reported in this articles are pseudonyms) and Robert were two participating teachers who were selected as positive examples for elaborate model use in biology instruction. Also selected were Julian, Michael and Maria whose PCK values as well as elaborate model use in biology instruction were both lower than those of other participating teachers.

The five participating teachers who were included in our qualitative analysis were similar in a number of aspects. All the teachers taught the subjects biology and chemistry at secondary schools in Bavaria, a federal state of Germany. The teacher preparation programs are directed by the federal states in Germany [94]. Therefore, all the teachers had similar teacher preparation with regard to their pedagogical and content knowledge training and a two-year long practical training in secondary schools [95]. Robert, 37 years old, and Tom, 40 years old, were two participating teachers above the average age of our overall sample (M = 35.9, SD = 8.5). Robert had a teaching experience in biology of five years, and Tom had a teaching experience in biology of nine years. By contrast, Julian (aged 29), Michael (aged 28) and Maria (aged 29) were younger teachers with limited teaching experience. Julian had been teaching biology for three years, Michael for two years and Maria for one year. At the time of data collection, Robert, Julian and Maria taught the subject biology in 10 or more lessons per week. Tom and Michael had a shorter experience of teaching biology at school (six lessons per week). Robert assessed his teacher preparation with respect to content knowledge as very good (equivalent to grade 'A'); however, he assessed it with respect to biology education as sufficient (equivalent to grade 'D'). Michael's and Maria's teacher preparation was evaluated as good (equivalent to grade 'B'). Tom and Julian described their teacher preparation in average as satisfactory (equivalent to grade 'C'). They did not make any statements about their attendance of professional development programs. The description of the five teachers is summarized in Table 6.

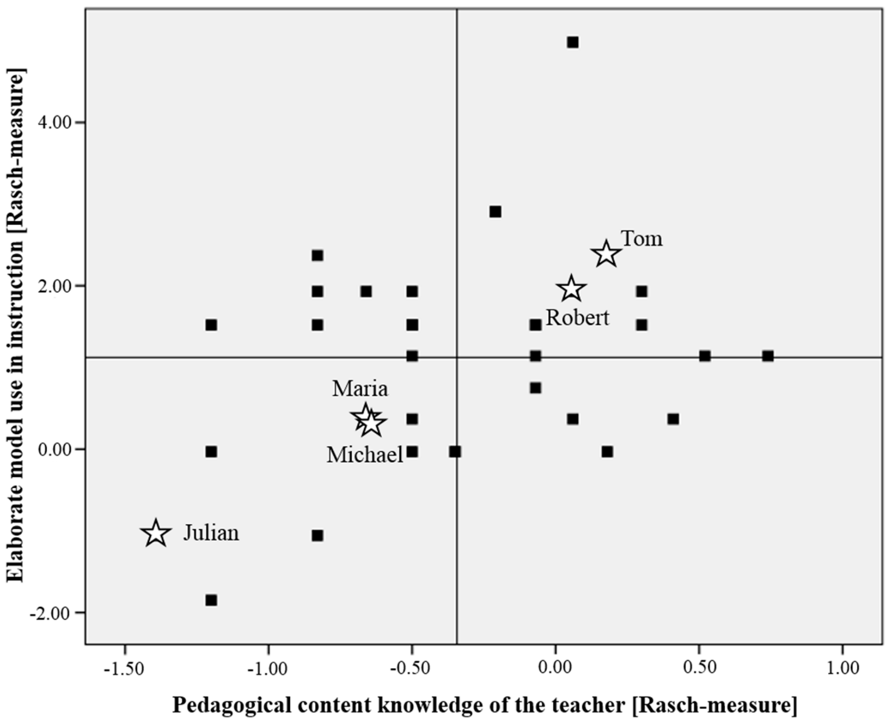

Figure 3. Selection of five teachers for the qualitative analysis of the model use based on their PCK and ELMO mean scores.

Table 6. Information about the five selected teachers and their opinions for qualitative analysis.

	Tom	**Robert**	**Julian**	**Michael**	**Maria**
Age	**40**	**37**	**29**	**28**	**29**
Teaching experience in years	9	5	3	2	1
Taught subject besides biology	chemistry	chemistry	chemistry	chemistry	chemistry
Evaluation of their teacher preparation in biology education content (biology)	sufficient (D) * sufficient (D)	sufficient (D) very good (A)	satisfactory (C) sufficient (D)	good (B) good (B)	good (B) good (B)
Number of lessons per week teaching biology	6	10	15	6	15
Topic of their selected lessons	accommodation in the human eye	structure of the human eye	structure and function of the human spine and spinal cord with the context of paraplegia	reflex	reflex

Note: * Grading system of Germany is stated with equivalence of US grading system given in brackets.

3.2.2. Lessons

In addition to the selection of teachers based on their PCK and elaborate model use, we selected lessons with the use of similar models for describing positive and negative examples. All selected lessons were planned for a time slot of 45 min. In Tom's and Robert's classrooms, the topic of both lessons was the 'structure and function of the human eye'. More specifically, the topic of Tom's lesson was about the process of accommodation of the human eye. Tom started the lesson by referring to an earlier lesson where the students learned the anatomical structure of the eye by dissecting a porcine eye. Afterwards, Tom used an optical bench to illustrate how changing the distance between a lens and an object leads to a sharp picture on the screen. He compared this process with an objective of a camera. After this introduction, he worked out the content of the lessons using a physical functional model of accommodation (see Figure 4).

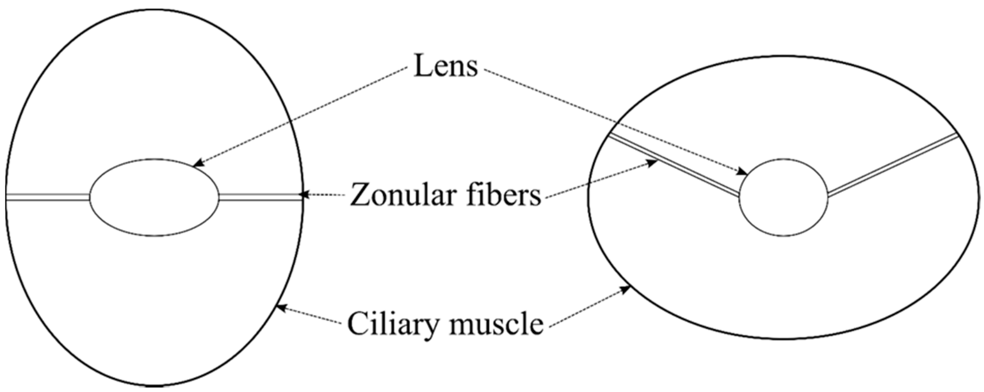

Figure 4. Schematic drawing of the three-dimensional physical model of accommodation used in the case lesson of Tom. Zonular fibers are highlighted in red in the used model. The situation on the left represents the process of focusing on distant objects, whereas the situation on the right represents that on near objects.

In Robert's lesson, the topic was the structure of the human eye. Therefore, Robert used a physical structural model of a human eye, which can be separated into its individual parts. The topic of Julian's lessons was about the structure and function of the human spine and spinal cord with the context of paraplegia. Michael and Maria taught the topic reflex. Julian, Michael as well as Maria used physical structural models of a human spine and spinal cord in their lessons.

At the beginning of Michael's and Maria's lessons, they worked out, together with their students, a general definition of reflex and the sequence of reflex. One important part of the reflex arc is the spinal cord. With the help of the model, they explained the structure and position of parts of the reflex arc. Julian started his lesson with the description of several neuronal connections which he mentioned in the previous lesson. Afterwards, the students watched a video film of a person who is paraplegic and then discussed what different life the paraplegic person has. Next, Julian used the structural model of the human spine and spinal cord to explain consequences of injuries at different spinal cord areas.

3.2.3. Aspect 'Characteristics of the Model'

This aspect contains the categories 'level of abstraction', 'level of complexity' and 'fitting to the learning goal' (see Table 1). When Tom used a functional model, he selected a model which fitted his learning goal—the process of accommodation. Concerning the 'level of complexity'. He focused on teaching relations within the topic process of accommodation, for example, the relation between contraction of the ciliary muscle and the shape of the lens. The selected model also highlighted relations, and therefore, fitted the complexity of the learning goal. In contrast, a structural model which shows all components of the human eye—and therefore single facts—would not fit Tom's learning goal. Additionally, the 'level of abstraction' of the model fitted his learning goal, because the components, which are irrelevant to the process of accommodation, were not shown. Maria's model was a structural model, which showed the structure of the human spine and spinal cord. Through the model, several aspects or single facts ('level of complexity') of the real object could be illustrated within a low level of abstraction ('level of abstraction'). However, the learning goals of Maria's lesson were the general description of the reflex and its sequence exemplified by the knee jerk reflex. The structure of the spinal cord as the nerve center was discussed by means of a worksheet. As a result, the used model in Maria's lesson seemed redundant and unnecessary for reaching the learning goal of her students. In Michael's lesson, the situation was similar. He also used a structural model which showed the structure of the human spine and spinal cord to describe one main characteristic of a reflex and the reflex arc. The structure of the human spine and spinal cord was also illustrated through the model, but discussed using a schematic drawing. However, Michael did not highlight any relation between the model and the schematic drawing.

3.2.4. Aspect 'the Way the Model Is Integrated into Instruction'

For this aspect, the categories 'introduction of the model', 'students working with the model' as well as 'purpose of the model' were taken into consideration. Tom introduced the model in detail at the beginning of the lesson. He not only named the content of his teaching, which was illustrated by the model, but also explained the models' components and how the model operates:

> Tom: [Tom takes a model of accommodation (see Figure 4) from the desk.] This is a model, which illustrates the situation. This wire represents the lens. And these red threads represent the zonular fibers. By pulling here, the ciliary muscle can be changed—so this structure on the outside represents the ciliary muscle. [. . .]

Robert also introduced the model at the beginning of the lesson. First, he linked the topic to those in the previous grades. Next, he named the model and its intended purpose. Then, Robert started with the outer structures of the eye and asked his students for the respective functions while they were working with the structural model.

In contrast, Maria and Julian did not name and describe the used model before working with it:

> Maria: The spinal cord is hidden in the spine. Yes . . . I brought something with me. Please, just take a short look at the model. We will need this view later. Yes? [. . .]

Both teachers talked about the content, which the students should learn. They ignored the integration of the model in teaching. As a result, the students did not consider the purpose of the model for learning the content.

Michael introduced the model in a very short way. He named the model and then directly started to work out the individual structure of the spinal cord:

> Michael: Good [with regard to the content he previously dealt with]. This is [takes the structural model of spinal cord] a specific cross section of the spinal cord. Where is the spinal cord located?

When we analysed our selected cases according to the category 'students working with the model', we identified that Tom involved his students in the teaching process during the whole phase of model work. In the following example, he formulated instructional tasks, in which his students had to apply the taught content:

> Tom: Okay. The lens takes a round shape. Now, think about when you are reading or watching television or playing computer games. Which is more exhausting, playing computer for one hour or taking a walk and looking at the landscape?

During the lesson, Tom provided many instructional tasks, which are on a higher level than recall of factual knowledge. Both Julian and Michael involved their students while working with the model and their students were asked to work actively with the model in the lessons. However, both teachers did not formulate elaborate questions in comparison with Tom while working with the model. Both teachers requested from their students a higher number of short answers to the questions on the factual recall level. In Maria's model use work, students were not actively involved in the learning process. Maria described the structure of the spinal cord by means of the model on her own as a lecture. At the beginning, she only gave her students the note that they will need when following content later in the lessons. Then, her students only had to listen to her and did not have to do further instructional tasks on what they had learned from the model.

How models were integrated in teaching practice was analyzed in the third category 'purpose of the model'. Tom used the model not only for illustration, but also as a tool for scientific inquiry. For example, when Tom made changes to the model, he posed to the students questions about the impact of those changes.

> Tom: [Tom takes the model of accommodation.] In this situation [see left part of Figure 4], the ciliary muscle is large and relaxed; the zonular fibers are stretched tight. What consequences would this situation have for the lens?

Additionally, he used the model to predict the changes in the human eye during the process of focusing on a distant object.

> Tom: [. . .] So, which case would this situation [see left part of Figure 4] be?

> S13: Looking into the distance.

Michael used his model only for illustration. In class discussion, the structure of the spinal cord was worked out. He showed several structures of the model and his students should give short answers about what the structures are called. Michael did not ask his students to do instructional tasks, in which students should transfer the learned content to a new situation. Relations between structure and function were not highlighted. In contrast to Michael's model work, Julian wanted to use the model to talk about the real object, however, he did not actively involve the model. Julian asked his students about the consequences of injuries at several points of the spinal cord and pointed to different positions of the model. However, the instructional task was posed in a general way without any relation to the used model:

> Julian: Okay. This means, when a person has paraplegia or a biker fall on a specific position of the spinal cord . . . Nerves are cut, in the drastic case, . . . are compressed, that the neural impulses are not transmitted any longer. Yes, there are several possibilities. This can happen at this point [pointed at the model]. This can happen at another point [pointed at another position of the model] and this can also happen at this point [pointed at a third position of the model]. Which consequences will you expect? . . . Injuring the spinal cord at specific positions?

Julian did not place any value on relating students' answers to the model. He also engaged students in this instructional task without pointing at the model and specific positions of the spinal cord.

3.2.5. Aspect 'the Way the Model is Used to Foster Scientific Reasoning'

This aspect included the categories 'predict scientific phenomena' as an emerging scientific research question or hypothesis, 'revise models' as a relation to models, and 'critical reflection' of models. In Maria's lesson, her model seemed to be unnecessary for learning the content. At the beginning of the lesson, the scientific research question 'What are actually reflexes?' was posed by Maria. During the lesson, she worked out all essential characteristics of reflexes and explained the structure of the spinal cord to her students using a worksheet with an illustration. The used model of the spinal cord and spine was out of place because Maria did not mention the model any more when she referred to the scientific research question that was posed. She only mentioned relations to the worksheet. Tom used the model in a contrasting way. At the end of the lesson introduction, Tom formulated a scientific research question, which was to be answered by revising the model:

> Tom: For getting a sharp picture, I change the distance between the objective and the focal plane. This is how it works in our model and in photography. But we can't change the position of the lens in our eye that is what we would have to do, if we want to do it by analogy [Tom points to the optical bench]. [. . .] So what do you think about how it works in our eye?

During the lesson, Tom gave several elaborate instructional tasks to his students. By means of these tasks, he related the different aspects of the content to the formulated scientific research question. He used only a small number of factual recall tasks, and tasks which required short answers.

The models the teachers used gave them possibilities to reflect on the models critically. Tom tried to critically reflect on his model by showing parallels between the components of the model and structures of the human eye.

> Tom: [. . .] This wire represents the lens. And these red threads represent the zonular fibers. By pulling here, the ciliary muscle can be changed—so this structure on the outside represents the ciliary muscle [. . .]

While working with the model, he also highlighted the limitations of the model.

> Tom: [. . .] Now, we assume the muscle becomes tense; it contracts and gets closer around the lens, thereby it gets thicker—we can't see it in this model—but what can we see?

The critical reflection on the model used in instruction also seemed to be important for Robert. He started with the outer structures of the eye and asked his students for the respective functions. In doing so, he focused on differences between the eye model and the real object. When he separated the eye model into its individual parts, he emphasized that this would not work with a real eye:

> Robert: Right, the cornea, which is a part of the sclera, is pervious to light. I can remove it here. It would not work with a real eye in this way.

Robert: [. . .] and in here, there are two further structures in the eye. Usually you can't take them out that easy, but in the model it works.

Additionally, when Robert discussed the lens and the vitreous body of the eye in class, he told his students that the real structures are made from different materials:

Robert: Right, this structure is called vitreous body, because it is transparent. In reality, it is more jelly-like or gelatinous. It is not as tough as in this model.

Robert: So, if someone wears glasses, it is like a glass or synthetic lens. In this model, it is also a synthetic lens. In reality—we will see it clearly, when we dissect porcine eyes—the lens of our eye is not tough like in a camera, but it is flexible. If I press the lens, it distorts.

As the third point, Robert stressed that the model has a different appearance compared to the real object. Additionally, he explained where the model is located in the human body and referred to the adjoining structures, which were not shown in the model.

Robert: In the model, we can see another structure from outside. We can't see it at our own eyes, but here in the model it can be clearly seen.

S15: The optic nerve.

Robert: Right, that is actually the part which leads to the brain.

Maria started with a brief mention of the differences between the spinal cord model and the real object:

Maria: [. . .] Please, just take a short look at the model. We will need this view later. Yes? . . . The spinal cord looks like this, more like this model.

However, she did not include further aspects while describing the structure of the model. The location or the different material of the model of the spinal cord used are some further aspects that could be mentioned during Maria's model work. Julian and Michael did not critically reflect on their used models. For Robert and Michael, they both described the structures of the human eye and the spinal cord, respectively. Robert used the specific structures to mention different aspects, on which he can reflect critically during the model work. However, Michael only focused on the content, which his students should learn, and on the specific biological terms.

3.2.6. Further Observations

During the qualitative case study we noted several other aspects of teaching. One conspicuous difference between our extreme cases (Tom and Robert vs. Julian, Maria, and Michael) was that Tom and Robert provided more instructional tasks on a higher cognitive level than those on recall of factual knowledge. The cognitive level indicates the processing strategy, which a student needs to solve a given task [6]. Students of Michael, Julian and Maria mainly had to give short answers, for example, just one word without explaining their answer. Models used in Tom's and Robert's lessons played a major role in students' learning of the content. Furthermore, the kind of model—structural or functional model—supported the possibility to implement several variables of ELMO, especially for the aspects the way how the model is integrated into instruction and the way the model is used to foster scientific reasoning. Michael, Julian, and Maria all used structural models but hardly implemented some categories of both aspects. The functional model selected by Tom enabled him to provide more elaborate instructional tasks for his students. It seemed to be easier for Tom to ask about changes in the model and their consequences. Additionally, when content was taught with two different instructional materials, for example, a worksheet and a model, both were not, however, connected to each other and, therefore, the used model seemed to be unnecessary.

3.3. Summary of the Results

In the quantitative phase of our study, we could identify that PCK as well as CK have no direct effect on students' achievement in the post-test. Furthermore, only PCK showed an indirect effect on students' achievement in the post-test mediated by instruction, more precisely by ELMO.

The qualitative analysis of the selected extreme cases initially showed the observability of all developed categories of ELMO and their several characteristics. Especially in the categories, which were related to the use of models as tools for scientific inquiry, main differences were shown between the different lessons for the introduction of and critical reflection on the model, as well as for illustration and scientific inquiry using the model. As indicated by the qualitative analysis of the teachers' instruction, the models seemed to be more integrated in their teaching.

4. Discussion

4.1. Contributions of the Study

The results of data analyses and interpretations indicated that the findings of this study are likely to make important contributions to the understanding of elaborate model use (ELMO), effects of teachers' knowledge on their model use, and the effects of ELMO on students' achievement.

The test instruments used in this study showed satisfactory objectivities and reliabilities. Furthermore, the fit values of our calculated models were good [84], although we had a relatively small sample size for our multilevel analyses.

4.1.1. Contribution to the Understanding of Elaborate Model Use in Biology Instruction

This study developed an approach to describe how teachers can work with models elaborately in instruction. Based on the literature, we devised an objective and reliable category system including several categories for measuring and describing elaborate model use in biology instruction (e.g., [9,15,75]). Each category consisted of different characteristic values. Our qualitative data confirmed that these theoretical values could be observed in videotaped biology instruction. These observations indicated a high content validity of our measurement. The highest characteristic values in our categories were identified in the lessons of Tom and Robert whom we selected as positive cases in our qualitative phase of the analyses. Low and medium characteristic values were observed in the lessons of Julian, Michael, and Maria. Based on the three aspects of ELMO and the several categories of each, the following points may be most important for teachers to pay attention to when working with models in the classroom (research question 1 and 3):

1. Before working with models in instruction, it is important for teachers to become clear about what content they want to teach and to define an appropriate learning goal. Based on this learning goal, they may select an appropriate model (see the first aspect and its three categories in Table 1);
2. A clear introduction of the model at the beginning of the model use may highlight the importance of the model for learning the content. Teachers can name the model, the components of the model, how the model works, and the content, which should be worked out using the model. In this way, the model seems as an independent teaching tool in instruction (see the second aspect category 'introduction of the model' in Table 1);
3. When models are used as tools for scientific inquiry, phases of model work include more cognitively activating instruction and impart a higher level of understanding of models and modeling science. Therefore, it is important to formulate and refer to scientific research questions or hypotheses as well as to ask students about consequences when making changes to the used model. On the one hand, students are more involved in the modeling process and model work. On the other hand, instructional tasks are on a higher cognitive level (see the second aspect category 'purpose of the model' in Table 1);

4. Critical reflection on the used model is important for supporting the process of scientific inquiry within model work. Several aspects are possible to reflect on. Teachers have the possibilities to discuss structural and material differences between the model and the real object, locations in the real object, adjoining structures, which are not illustrated in the model, as well as what is possible to do with the used model compared with the real object (see the third aspect category 'critical reflection' in Table 1).

By identifying typical examples for the different characteristic values, we found that our qualitative data provided different authentic examples for researchers and teachers to understand ELMO in a better way. Based on these examples, researchers and teachers can orientate themselves on how to use models when teaching biology, especially neurobiology. In accordance with the demands of National Education Standards (e.g., [2,3]), it is important to give in-service teachers several indications of how models can be used for scientific inquiry. Upmeier zu Belzen and Krüger [9] argue that teachers mainly use models for illustrating several aspects of a real object, but hardly use them as tools of scientific inquiry in science classrooms. Our ELMO framework focuses on this integration of scientific inquiry during model work (see the third aspect the way the model is used to foster scientific reasoning in Table 1). These suggested teaching practices can help teachers to implement models as one way to practice scientific inquiry in their classroom. Additionally, these practices may improve teachers' understanding of models and modeling in science [16] and, therefore, teachers can also develop their students' elaborate understanding of models and modeling in science.

4.1.2. Contribution to the Analyses of Effects of Knowledge Dimensions on Instructional Quality Features in Biology

Results of some studies indicated that preservice and in-service teachers have limited and divergent knowledge about models and modeling in science [25,48,51]. The reason for this limited knowledge is that there is a lack of opportunities for teachers in instruction to gain experiences of how to use models in science instruction [16]. However, hardly any previous studies have analyzed which dimension of teachers' professional knowledge affects the way teachers use models in instruction. Our results showed that teachers' PCK had a significant positive effect on ELMO, but CK had no significant effect. Several studies have already shown the effect of PCK on different instructional quality features (e.g., [60,61]) (research question 2). However, these studies focused on general instructional quality features. In biology education, the use of models is a subject-specific teaching strategy [24]. As PCK includes as one main facet the knowledge about teaching strategies and representations [24,40–42], its effect on ELMO seems a logical consideration. According to Shulman [44] (p. 8), PCK "is uniquely the province of teachers, their own special form of professional understanding" and subject-specific. For each subject, teachers have to know specific teaching strategies and in which way they can use them in instruction. Although our results showed no significant effect of CK on ELMO, we consider that CK is necessary for high-quality instruction. Current literature states that CK may be important for developing PCK [96–98]. Findings from biology education research already showed indications that teachers' CK is a prerequisite for their PCK, meaning that teachers need a high level of CK to develop an elaborate body of PCK [99,100]. Accordingly, for using models elaborately, teachers' domain-specific knowledge has to be improved through professional development initiatives and preservice teacher education at the university level.

4.1.3. Contribution to Fostering Students' Achievement

Several intervention studies already showed a positive effect of model use compared to other teaching materials (e.g., [17–20]). In this study, we could also show that the quality of model use is an important factor for fostering students' achievement, as we identified a significant positive effect of elaborate model use (ELMO) in instruction on students' achievement (research question 2). Therefore, we can conclude that not only the use of models fosters students' achievement, but also the quality of the model's use is crucial for fostering students' achievement. Working with models provides teachers opportunities to think about scientific phenomena from different perspectives. Results of our achievement tests showed positive effects of working with models on students' learning of factual knowledge like recalling learned facts as well as on their conceptual understanding of the learned content [81]. For solving tasks on conceptual knowledge, students need a deeper understanding of conceptual ideas and of the relations between several aspects of the learned content [81]. These aspects support students' learning as well as their understanding of science.

Models of effective learning in previous studies additionally described an indirect effect of teacher variables on student variables mediated through several instructional quality features (e.g., [58,61]). Based on this assumption, we formulated our hypotheses. Although we confirmed our first hypothesis, we could not identify a direct effect of teachers' PCK or CK on students' achievement in content knowledge in the post-test. Our result is, therefore, in line with models of effective learning [58,61]. We also confirmed our second hypothesis, and the indirect effect of teachers' PCK on students' achievement in the post-test mediated through ELMO. However, we also could not identify this mediation effect of teachers' CK.

The three ELMO aspects mentioned above showed how a teacher's PCK is expressed through his way of implementing model work in instruction. Our study found that this teaching behavior led to higher students' achievement. Through a clear introduction of a model, students seemed to be more focused on what is important for learning the content. Tom and Robert's students were also encouraged to explain different learning content areas and changes of the model. As a result, their students had to think about the content in an elaborate way and were more cognitively activated in the classroom than the students of Maria, Julian, and Michael. Several studies in different subjects already showed that cognitively activating instruction fosters students' achievement (e.g., [61,101]) because cognitive activation might lead to a deeper understanding of the content [102]. These studies used an overall rating to measure the level of cognitive activation in the whole lesson. Our qualitative analysis also identified several points of cognitive activation for a specific teaching strategy, particularly for model use in biology: (1) A clear introduction, (2) critical reflection to avoid the development of students' misconceptions (especially in Robert's lessons), and (3) demand for elaborate student answers.

Additionally, Robert's and Tom's instructional tasks in accordance with the framework of model use were on a higher cognitive level. On the other hand, Julian and Michael asked their students mostly about structures of the used model and their answers were short. It has already been shown by [103] that instructional tasks on a higher cognitive level foster students' conceptual knowledge defined as the knowledge about the relation between several facts [78]. Higher cognitive processing supports deeper processing of the content [104]. Given that Robert's and Tom's students became more involved in the model work with the changes in their used models, their students had the possibility to develop a more elaborate understanding of models [9,15,56]. A deeper understanding of models in science leads to a deeper understanding and also processing of the learning content and, consequently, to a higher students' achievement [105–107].

Therefore, we can conclude that the elaborate model use (ELMO) is an effective teaching strategy and mediates the effect of teachers' PCK on students' achievement in biology. This way of using models in instruction may lead to deeper processing of the content, a higher cognitive activation in the instruction and an elaborate understanding of models and modeling in science.

4.1.4. Contribution to the Research Field

Results of previous research showed several effects of teachers' professional knowledge dimensions on instructional quality features as well as effects of instructional quality features on students' outcome. However, there are only a few studies which analyze the chain of effects between teacher, instruction, and student as a whole (e.g., [108]). In this study, it was possible to videotape biology lessons in order to analyze such chain of effects for the biology-specific instructional quality feature 'use of models'. The studies mentioned above paid attention to general instructional quality features, for example, cognitive activation. Our study analyzed this chain of effects for a domain-specific instructional quality feature. Such analyses were hardly conducted before our study. Moreover, we could identify positive effects of teachers' professional knowledge dimensions—mediated by a domain-specific instructional quality feature—on student outcome, whereas recent studies only analyzed general instructional quality features in this context [60,61]. By the independent measurement of teachers' PCK and CK, we could comparatively analyze the predictive validity of teachers' PCK and CK. Our results supported those of other studies, in which teachers' PCK had an effect on instruction and student outcome in contrast to the effect of their CK (e.g., [61,109]) (research question 2). Furthermore, our results showed the importance of qualitative aspects in using models. Previous studies have already shown that models have effects on students' learning in comparison learning without teaching tools (e.g., [17,18,56]), but a qualitative consideration of model use was not carried out. The use of models according to aspects of scientific reasoning (e.g., [2,7]) has an effect on students' content knowledge. Thus, not only the use of models, but also the way of using models in instruction is important for students learning. Furthermore, the implementation of German NES [2] in biology instruction with model use to foster students learning will be even more important.

4.2. Limitations

As our study had some limitations, the results have to be interpreted with caution.

4.2.1. Selection of Our Quantitative Sample

As teachers participated voluntarily in our study, we did not have a randomly selected sample. However, after each lesson, teachers were asked if the videotaped lesson was similar to their usual instruction, and the majority of the teachers confirmed this. Besides this, our total sample consisted of relatively young teachers with limited teaching experience in years (M = 6.3, SD = 5.8).

4.2.2. Model Use in the Videotaped Lessons

In our quantitative and qualitative analyses, we only took three-dimensional physical models into consideration. In our knowledge test to capture teachers' PCK, only items concerning three-dimensional physical models were included. For a validity measurement, we only analyzed this type of model. Two-dimensional models, diagrams, and mental models [110] were disregarded. Furthermore, our analyses were based on two videotaped lessons of each participating teacher. In these videotaped lessons, we only analyzed a small section of the teaching. Therefore, identifying teaching patterns or drawing general conclusions should be done with caution. Additionally, the categories in our developed category system and the examples provided were each about one possibility to use models effectively in biology instruction. However, for using models effectively in biology instruction, it is not only decisive to implement each described category, but also to integrate several categories and aspects appropriately in instruction. Therefore, a clear structuring of the lessons will make it possible for the instruction to foster students' learning [58].

4.2.3. Teachers' Professional Competence

Besides PCK and CK, teachers' professional competence also includes pedagogical knowledge (PK) as an additional knowledge dimension, and non-cognitive aspects such as beliefs and motivational orientations [94]. These aspects of teachers' professional competence were not included in this study. Effects of PK and also non-cognitive aspects on features of instructional quality were already identified in other studies (e.g., [61]). Therefore, additional aspects of teachers' professional competence have to be taken into account in further studies. Adding further aspects to the analyses could result in a higher percentage of explained variance of ELMO than the 13%, which were already explained by PCK and CK in this study. In addition, the effects of different facets within teachers' PCK on the use of models should be analyzed in further studies. These facets were also operationalized by researchers in recent studies (e.g., [46]). Further studies in this research field should provide more information of those facets of PCK about models that are useful for teachers' effective use of models in instruction.

Supplementary Materials: The following are available online at http://www.mdpi.com/2227-7102/8/3/118/s1, Dataset S1: Means of the variable.

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