sustainability

MDPI

Article

Effects of Teacher Training in Systems Thinking on Biology Students—An Intervention Study

Stefan Streiling *, Christian Hörsch and Werner Rieß

Department of Biology and Pedagogy of Biology, University of Education Freiburg, Kunzenweg 21, 79117 Freiburg, Germany; hoersch@ph-freiburg.de (C.H.); riess@ph-freiburg.de (W.R.)
* Correspondence: stefan.streiling@ph-freiburg.de; Tel.: +49-(0)761-682-307

Abstract: Systems thinking provides many advantages in solving complex scientific, economic and sociocultural problems in the field of education for sustainable development. Various studies have shown that systems thinking can be promoted in students at all levels of school education. Previous studies have mainly focused on how to directly develop and support systems thinking in students. The present study focused on biology teachers by investigating the extent that their content knowledge (CK) and pedagogical content knowledge (PCK) augments systems thinking in students attending biology classes. On the basis of the finding that content knowledge (CK) and pedagogical content knowledge (PCK) are an essential aspect of any type of training, we investigated in a teacher training program the effects of varying amounts of CK and PCK to the ability of biology teachers to foster systems thinking in students. Therefore, a quasi-experimental intervention study was implemented in a pre- and posttest control group design. The results revealed that biology teacher training can sufficiently improve systems thinking in biology students and that PCK plays an at least equally important role as CK in promoting systems thinking.

Keywords: systems thinking; teacher training; education for sustainable development

check for updates

Citation: Streiling, S.; Hörsch, C.; Rieß, W. Effects of Teacher Training in Systems Thinking on Biology Students—An Intervention Study. *Sustainability* **2021**, *13*, 7631. https://doi.org/10.3390/su13147631

Academic Editor: Marc A. Rosen

Received: 20 May 2021
Accepted: 3 July 2021
Published: 8 July 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Since the beginning of the industrial age, technological progress has contributed to a rapidly increasing world population. This growth entailed a corresponding rapid depletion of natural resources. The WWF Living Planet Report [1] lists species extinction, environmental disasters, overfishing, water scarcity and extreme weather conditions as possible consequences of this development. According to the report's forecasts, our ecological footprint is growing at such a fast rate that by 2030 two planets would not be enough to satisfy the needs for food, water, energy and other natural resources, and by 2050, humanity would require an equivalent of three planets. At the 1992 summit in Rio de Janeiro, the international community already agreed on the core objective of sustainable development: transferring this growth into an ecological, economical as well as socially sustainable system that benefits the whole of humanity and future generations. As a result, Agenda 21 declared education as a critical aspect "for promoting sustainable development and improving the capacity of the people to address environment and development issues" ([2], p. 320). This declaration is considered the birth of "Education for Sustainable Development" (ESD). In the following years, individual nations increasingly implemented ESD in their educational plans and school curricula especially for biology classes.

Various scientists (see, e.g., [3–6]) have considered systems thinking a key competence to be acquired through ESD in science education. The competence includes the ability to combine nature and culture and to develop corresponding problem-solving skills through systems thinking to be able to properly tackle the complex and dynamic issues of sustainability discourse. However, systems thinking still plays only a minor role in this area. To promote systems thinking in students, the call for an implementation of ESD into teacher training is essential. This paper discusses a training course for biology teachers about promoting systems thinking in biology class and examines its efficacy based on students' results.

2. Theoretical Foundation of the Study

2.1. From System Theory to Systems Thinking

In many scientific areas, systems theory is important for understanding complex relationships (see, e.g., [7–9]). In biology, for example, living beings are viewed as complex systems [10,11] that can be integrated into other systems, such as populations and ecosystems [5].

According to Bertalanffy [12] systems consist of individual elements that affect and are affected by each other. The complexity of systems is only limited by the large number of components. Their complexity can rather be explained by the strong and diverse interactions between elements and their integration into greater overall systems. Given the complexity of biological systems, they tend to be nonlinear and sensitive to initial and boundary conditions [12,13]. They are therefore difficult to calculate and to predict [14–16].

The concept of systems thinking comprises the cognitive skills needed to understand or predict reactions of complex systems. One major difference between systems thinking and non-systems thinking is that principles that are true for complex systems are involved in the cognitive analysis and representation of these systems [5]. Numerous other terms are often connected to systems thinking such as system-oriented thinking, ecological thinking, complex problem-solving or networked thinking. They are either used synonymously or have a similar meaning. Ossimitz [17] made a major contribution to understanding systems thinking by developing a four-dimensional concept that consists of (1) networked thinking (thinking in feedback loops), (2) dynamic thinking (thinking over time), (3) thinking in models and (4) system-compatible acting. Similar concepts can be found in [7,18–23]. Based on Ossimitz's [17,24] concept, Riess and Mischo [5] defined systems thinking as the skill to identify, describe and model (e.g., structure, organize) complex areas of reality as systems. This definition also includes the abilities to determine system elements and interactions, to understand and provide explanations for temporal dimensions (dynamics), make predictions and develop "soft" technologies based on one's own models. Riess and Mischo [5] described "soft" technologies as acting instructions that do not change the dynamics and thus do not destroy the emergent properties of systems.

2.2. Promoting Systems Thinking

Over the last 30 years, several studies have focused on promoting systems thinking in adults and students. The overall result is that systems thinking can successfully be promoted across different age groups (see, e.g., [3,5,18,19,25–29]). However, some authors [12,14,15] describe various difficulties due to the complexity or nonlinearity of systems, which are even difficult to understand by older students or adults.

Various methods have been proposed to promote systems thinking. Some used computer simulations to promote systems thinking in adults [30,31]. Computer simulations have also proven their merits in school environments of different age groups [5,32], but Riess and Mischo [5] found that computer simulations only had a positive impact in combination with traditional classes. Sweeney and Sternman [15] used stock and flow tasks to foster systems thinking in university students while others used ecological contexts or developed ecological and biological units [18,19,25–27,33,34]. They were able to show that systems competence consists of system organization and system properties.

In summary, children are more likely to be supported by experienced-based learning approaches in systems thinking, whereas with increasing age among adolescents and adults increasingly computer-based approaches are promising.

Ossimitz [17,24] showed in math classes that teachers play a vital role in improving students' systems thinking. These results correspond to Hattie's [35] important meta-analysis that showed that students' success primarily depended on the teacher's expertise, irrespective of school subject (see also [36]). Teachers are very important for avoiding misconceptions [37] in understanding complex systems at an early stage. Accordingly, we decided to develop a teacher training course and measure its success against student outcomes.

2.3. Heuristic Competence Model of Systems Thinking

In this study, we used a new heuristic competence model of systems thinking (see Figure 1), which was developed in parallel to this study by Rieß et al. [38]. The concept of systems thinking was described in detail in this competence model, which served as a foundation for successive interventions (particularly for teacher training) and as a testing instrument. This model is originally based on Riess and Mischo's [5] definition and the resulting first heuristic and structural competence model [25]. Another dimension was added to the model (evaluation of system models and results of model application). As a result, the current version distinguishes between four dimensions of systems thinking, each with four sub-abilities [38]. The first dimension describes basic cognitive elements of systems thinking, focusing on the concept of a system, on the principles of a systems-oriented view, on areas of reality, and on the characteristics of complex systems. The second dimension concentrates on abilities relating to the methods applied in system sciences to gain knowledge. This dimension especially emphasizes the abilities needed to understand and construct different types of system models. Based on the previous two dimensions, dimension 3 defines abilities that are needed when using system models to solve complex dynamic problems. Assessing the scope and limits of the findings obtained through modeling is essential in system sciences. The abilities needed for this assessment are listed in dimension 4. Additional information on the heuristic competence model and its formation can be found in [29,38].

Competence Dimensions/-Areas	Sub-Capability 1	Sub-Capability 2	Sub-Capability 3	Sub-Capability 4
Dimension 4: Evaluation of system models	The capability to determine the structure validity of system models (consistent with empirical evidence - observed values)	The capability to determine the validity system models (consistent with measured values) - Sensitivity analysis	The capability to determine the validity for application	The capability to determine the uncertainty of a forecast
Dimension 3: Solving problems using system models	The capability to asses the need of using a system model for processing a present problem	The capability to assess the type of system model (e.g. quantitative vs. qualitative), which is required to process a problem	The capability to give explanations, make predictions and to design technologies based on qualitative system models	The capability to give explanations, make predictions and to design technologies based on quantitative system models
Dimension 2: Modeling systems	The capability to determine system elements, interactions, subsystems, system boundaries, system hierarchies and the model purpose	The capability to understand and reflect a complex system with the help of a text field or a word model	The capability to read/understand qualitative system models. Construct/map effect-graph/-matrix	The capability to read and construct quantitative system models
Dimension 1: Declarative/Conceptual systems knowledge	Basic knowledge of systems theory (system concept, system structure, system behavior, sub-systems, ...)	Knowledge of areas that can be considered as systems (also knowledge of simple and complex systems)	Knowledge of system hierarchies (e.g., cell, tissue, organ, organism, population, biocenosis, ecosystem, landscape, biosphere, geosphere)	Knowledge of properties of complex systems (structural and dynamic complexity, non-linearity, emergence, self-organization, dissipative structures, system integrity, ...)

Figure 1. Heuristic competence model [38].

2.4. Promoting Systems Thinking through Teacher Training

Encouraging teachers to think systemically is essential for promoting systems thinking in schools. No courses on in-service teacher training have been previously developed. Thus, the literature lacks evidence to suggest which aspects to address when designing an effective teacher training course that promotes systems thinking. Nonetheless, various studies have suggested that teachers' knowledge, attitudes and beliefs should be the focus of empirical studies because of their positive influence on the learning successes of students (see, e.g., [35,39,40]). Others [41–43] postulated in this context the importance of content-related professional knowledge, which can now be found in national standards documentation for science teacher education (see, e.g., [44] Germany; [45] U.S.). Based on Shulman's [41] seminal article, teachers' professional knowledge is currently divided into the three domains: content knowledge (CK), pedagogical content knowledge (PCK) and pedagogical knowledge (PK) [46–49]. CK and PK are assigned to the concept of content knowledge and PK to the concept of non-content-related knowledge, which includes strategies and procedures for developing effective lessons. As researchers of biology didactic we are interested in different qualities of content mediation and therefore did not address PK in this study. According to Hashweh [42] teaching should be based on the complex interaction between the teacher, the subject and the student, which is part of pedagogical content knowledge. Therefore, we decided to focus especially on the concept of pedagogical content knowledge.

The heuristic competence model of systems thinking by Rieß et al. [38] is shown in Figure 1. In the context of this study, teachers' CK can be defined simply as a basic understanding of systems and the use of this knowledge to solve problems by using systems models. PCK can be seen as knowledge of how to foster systems thinking in students. No consensus has been established in recent studies on which domain of content-related professional knowledge is most important for students' science performance (see, e.g., [50,51]), although a long line of research has emphasized the importance of CK in the development of PCK [36,49,52–54]. Consistent with [41,55,56], we believe that PCK plays a vital role as a unique characteristic of the teaching profession by serving as a bridge between CK and PK. Ample evidence supports this assumption. Lipowski ([57], p. 399), for example, regarded teachers' CK and PCK as an important cognitive condition for deeper reflection about teaching practice and having a large influence on the development of teaching competences. Lipowski ([57], p. 389) also suggested basic characteristics that distinguish especially adult learners from children and teenagers (e.g., a wide repertoire of knowledge, skills, strategies and experiences). He concludes adult learning is primarily voluntary and rather self-organized. The motivation of adults increases with learning relevant content and the expected personal benefit.

Consistent with the reviewed literature, Mahler et al. [58] recommended that teachers have an expertise level of CK. Lipowski and Rzejak [59] argued for the need to deepen PCK and improve diagnostic skills. They also emphasized that an in-service training program should be sufficiently long (see also [60–62]), especially when implementing an input phase, trial phase and reflection phase ([59], p. 7), which have been found to be important aspects of successful in-service training [63–65]. Gräsel et al. [66,67], inspired by Deci's and Ryan's [68] self-determination theory, proposed to enhance teachers' creativity by providing ideas and materials instead of complete teaching concepts.

2.5. Resulting Aims and Hypotheses

The fundamental aim of this study was to investigate the extent that systems thinking can be effectively promoted in students by teacher training and which factors influence this outcome.

Summarizing the reviewed literature, three general conclusions can be drawn: (1) Basic knowledge of the promotion of systems thinking in students, as it was presented in the heuristic competence model of systems thinking (see Figure 1), is available. (2) General indications for successful concepts of teacher trainings exist, particularly about the importance of teaching content-based knowledge, coupled with knowledge about how to teach content-based knowledge. Furthermore, alternating between input and training phases seems to be very important, and short-term training programs proved to have little sustainability. (3) Researchers agree on the fundamental importance of teachers' abilities, skills and attitudes in influencing students' performance. In this context, researchers have often emphasized that teachers should have in-depth CK, especially in the natural sciences. However, no consensus has been achieved on the level of PCK that a successful teacher should have. For this reason, we decided to investigate the effect of PCK by varying the levels of CK and PCK in the training. We developed two different types of trainings. Training 1 emphasized a less strong base of CK and therefore more focus on PCK, and Training 2 emphasized a very strong base of CK and therefore less PCK.

To better evaluate the two different types of the teacher training, we decided to investigate the effectiveness at the student level. Consequently, we posed the following hypotheses:

1. A teacher training can successfully promote systems thinking in students.
2. Teacher training with proportionally increased PCK will better promote systems thinking in students.

3. Method

3.1. Research Design

Figure 2 shows the different stages of the quasi-experimental intervention study for which a pretest–posttest design was chosen. The period in which the study was conducted was February to March 2013. At the beginning of the study, all students participated in a pretest over a period of 2 to 3 weeks before teacher training. As part of the intervention, two experimental groups (EG 1 and EG 2) were formed, consisting of four and three teachers, respectively. The teachers of both experimental groups received training and subsequently prepared and implemented a teaching unit on systems thinking consisting of eight lessons for their students. Control group (CG) teachers neither received teacher training nor did they implement an eight-hour teaching unit on systems thinking. Instead, they adhered to the approved curriculum for biology in grade 9 during the time of the intervention. One to two weeks after the intervention and its subsequent teaching unit, the posttest was administered. Concurrently, sampling of the control group classes was conducted. All phases, pretest, intervention and posttest of the study, in which teachers as well as their students participated were supervised by the authors.

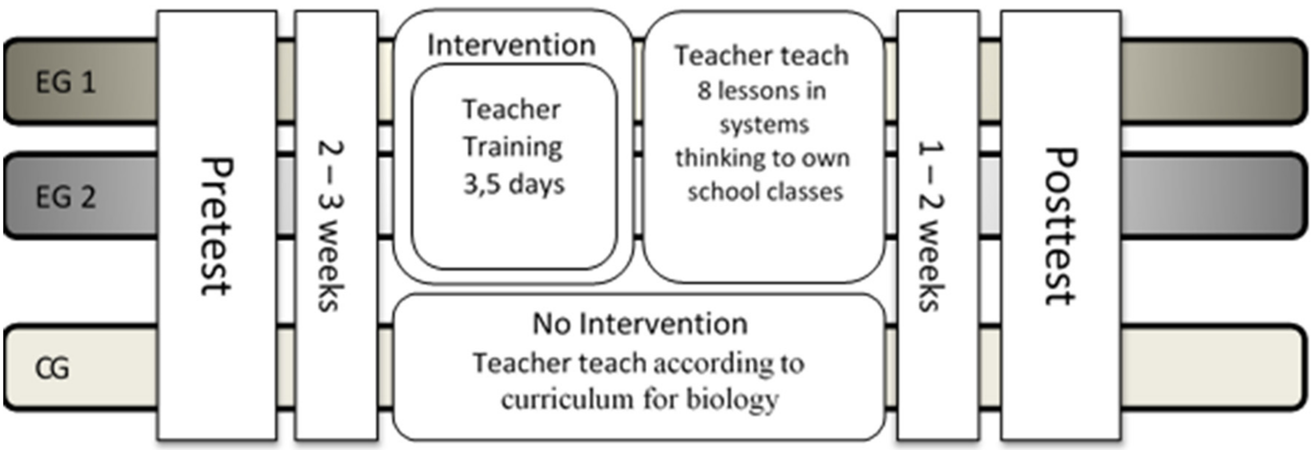

Figure 2. Different stages of the quasi-experimental intervention study.

3.2. Intervention

To answer the research question, the teachers participating in the intervention (see Figure 3) received 28 h of training on systems thinking over four days.

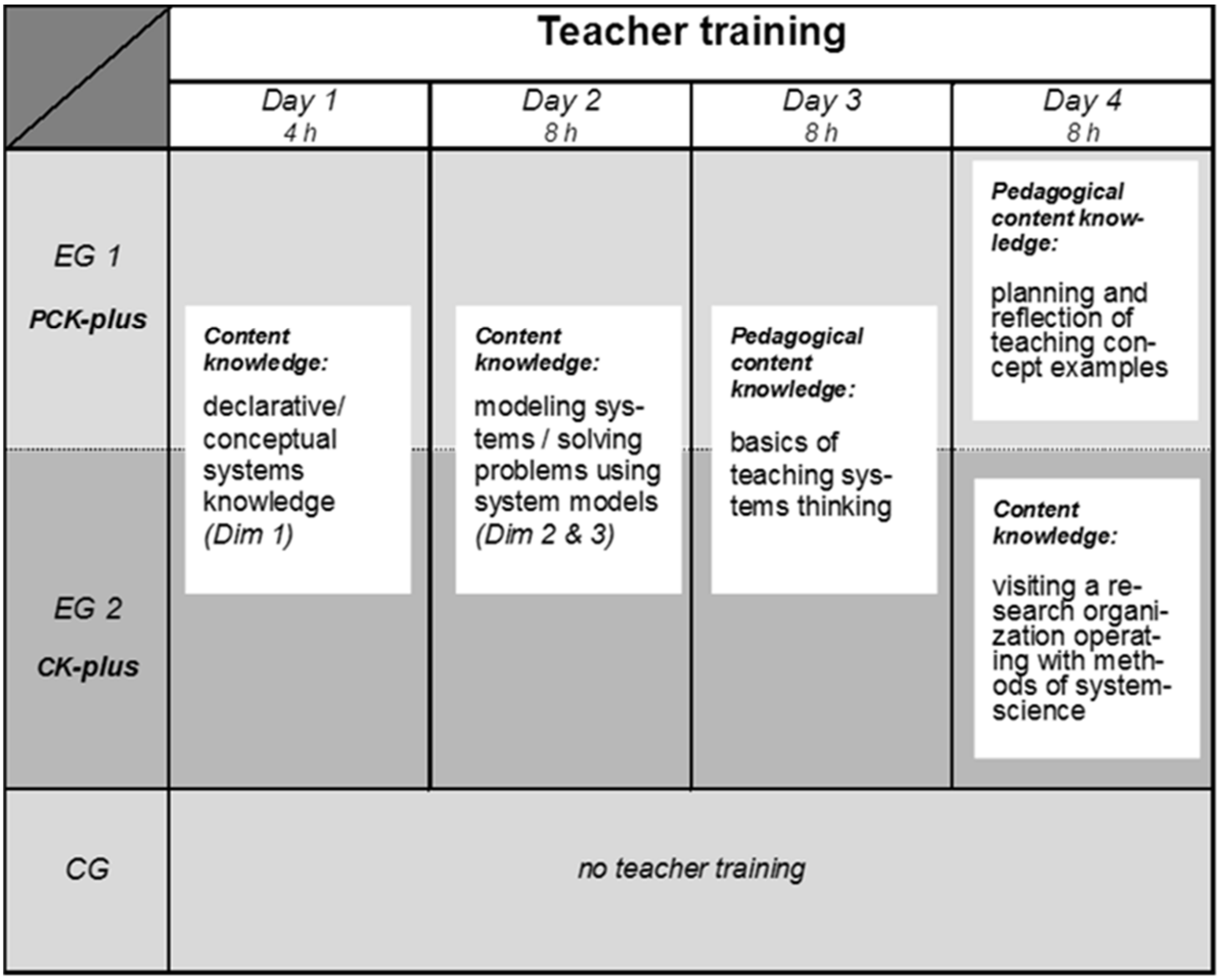

Figure 3. Overview of the teacher training program.

According to our hypothesis, experimental group 1 received 16 h of an advanced training on PCK and 12 h of a basic training on CK. In contrast, experimental group 2 received 20 h of advanced training on CK and 8 h of reduced training on PCK.

The first three training days were identical for both experimental groups (see Figure 3). The first training day consisted of a four-hour CK unit which provided the basic knowledge of systems theory that can be found in dimension 1 of the heuristic competence model according to [13,69]. The second training day also followed the same two authors' approach, teaching a CK unit in the fundamentals of how to analyze systems. Since the forest ecosystem is a prominent and illustrative example for a biological system, a forestry expert subsequently presented the system in detail. By introducing additional biological systems, such as the Lake Victoria ecosystem (according to [70]) and the biological system of the human body, participants learned about the diversity of biological systems that can be used in biology class. On day three, the PCK unit focused on the fundamentals of how to teach systems thinking. First, an overview of the current state of research on systems thinking and its promotion was given. At the end of the third training day, concrete teaching methods to promote systems thinking were presented and then applied by the participants using examples. The methods used in this context are, among others, based on Bollmann-Zuberbühler's [70] practical handbook "Systemdenken Fördern" ("Promoting Systems Thinking").

Following the maximum variation principle [71], the fourth training day was designed differently for both groups. Experimental group 1 received only 8 h of training on PCK, whereas experimental group 2 received training that focused purely on CK. During the training program, the teachers developed sub-capabilities that correspond to the sub-capabilities described in dimensions 1–3 of the heuristic competence model (see Figure 1).

On their final training day, experimental group 1 received an 8-h training unit inspired by Lipowsky and Rzejak [59] during which the participants independently prepared a teaching unit to promote systems thinking and discussed and analyzed its implementation together with the trainers. In accordance with Gräsel et al. [66], who sought to strengthen participants' initiative, ready-to-use teaching concepts were not provided in this unit. Instead, teachers were required to use ideas and elements developed previously. In contrast, experimental group 2 visited an institution that focuses on exploring the forest ecosystem and implementing the newly learned knowledge.

3.3. Sample and Implementation

The sample (N = 289) consisted of 9th graders attending biology classes at secondary schools in Germany of which 52.9% were female and 45.0% male (2.1% did not provide details). All participating classes were distributed into two experimental groups and one control group. Experimental group 1 (EG 1) comprised 70 students, experimental group 2 (EG 2) 111 students and the control group (CG) 108 students. The total number of biology teachers teaching the different student groups was N = 10. In this group there were 4 teachers for experimental group 1 (EG 1), 3 for experimental group 2 (EG 2) and 3 for the control group (CG). It consisted of experienced biology teachers (N = 7, 64% female) with a medium range of work experience from six to ten years. All teachers taught one or more ninth grade classes in Biology at secondary schools in the state of Baden-Württemberg (Germany) and were selected through a statewide call for application. Table 1 shows the allocation of students to classes and also detailed information about teachers.

Table 1. Sampling Distribution.

	EG 1	EG 2	CG	Σ
Students (N)	70	111	108	289
Classes (N)	4	6	5	15
Teachers (N)	4	3	3	10
Sex—Male (N)	1	1	2	4
Female (N)	3	2	1	6
Years of Work experience (Medium Range)	11–15	3–5	3–5	6–10

3.4. Measuring Instrument

The questionnaire, which we developed in 2012 and 2013 as part of this study, is an enhanced version of the measurement tool successfully used in 6th grade classes by the SYSDENA project [25]. It was adapted to the performance of 9th-grade middle school students by conducting a pilot with N = 72 students from December 2012 until January 2013. The piloting questionnaire (N = 72) consisted of 24 items (semi-open, multiple choice) with a total average difficulty of 0.39 (Min.) < 0.63 (p Mean) < 0.82 (Max.) and internal consistency of $\alpha = 0.69$. Items' discriminatory power was 0.06 (Min.) < 0.22 (Median rit). < 0.53 (Max.). This suggests that the preliminary measurement instrument was suitable to raise systemic thinking in students.

The questionnaire was intended to detect systems thinking quantitatively through a paper and pencil test. The topic was based on the forest ecosystem. Subsequently, it was extended to other areas of biology (e.g., nervous system in human biology) and also to natural sciences (e.g., physical systems) accessible to a systemic approach.

To focus the significance of each question on the ability of systems thinking, the questions were designed to be solved without larger content knowledge in the relevant biological topics. The processing time was limited to approximately 45 min. The dimensions and levels of expertise of the heuristic competence model (Figure 1) were used for the development and adaptation of the questionnaire used in the 9th grade. Multiple-choice items and a few half-open tasks were used for the specific detection of systems thinking.

Figure 4 shows an example of an effects diagram that assesses dimension 3, which represents the ability to solve problems using system models. System models, which play a central role in promoting systems thinking, are often represented by cause-and-effect diagrams (see, e.g., [70]). Therefore, these diagrams were central to many aspects of systems thinking. A plus amplifies and a minus minimizes the influence of one system element to another. A circle indicates a positive or negative feedback loop. The correct answers in the example would be A = F (false), B = F (false), C = R (correct) and D = R (correct). The questionnaire is available in the original language in the Supplementary Materials.

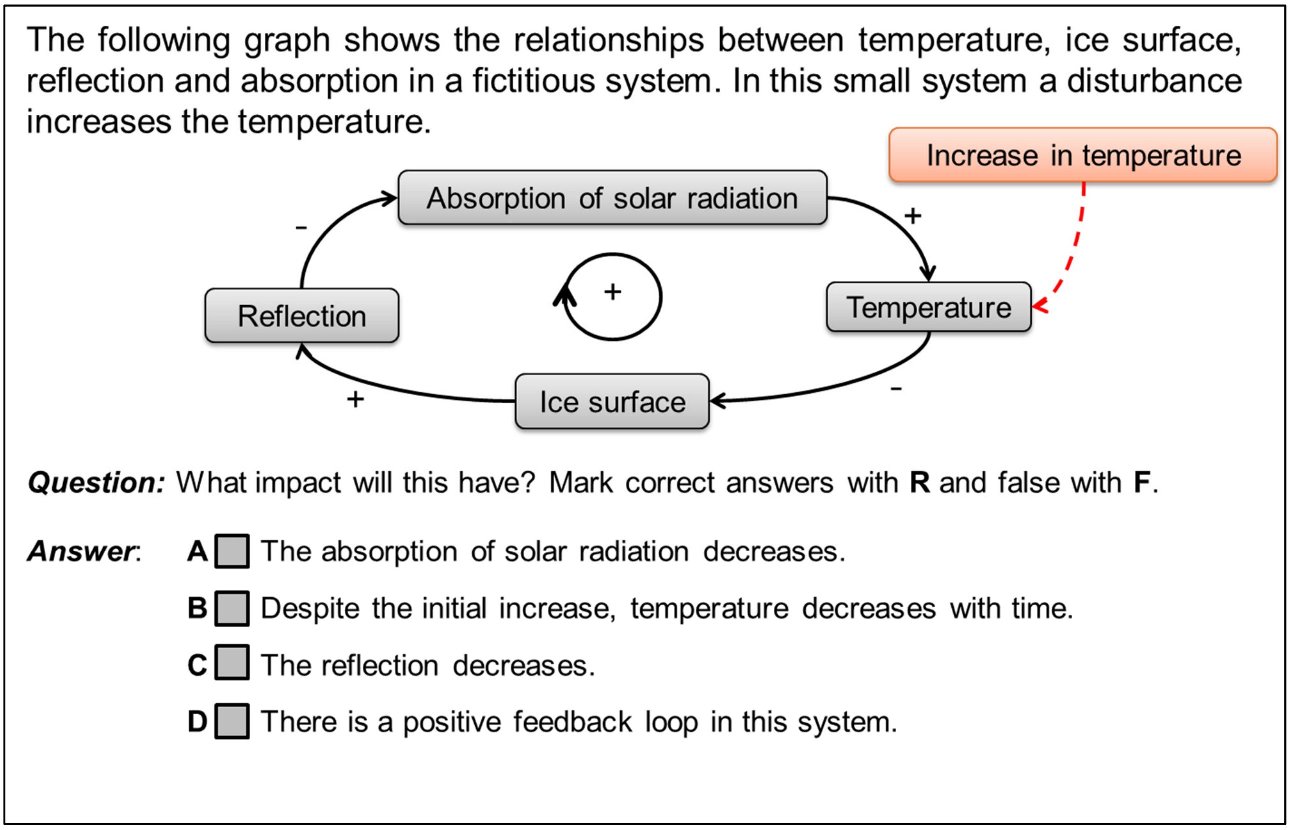

Figure 4. Example of a dimension 3 item (adapted from [25]).

Accompanying the covariates gender, age, and native language of the parents, as well as the trade marks in mathematics, German, and "NWA" (scientific work, includes: biology, chemistry and physics), academic self-concept (social reference norm by SESSKO [72]) and motivational orientation (after SELLMO [73]) were recorded.

4. Results

4.1. Psychometric Criteria

The internal consistency was $\alpha = 0.68$ for the pretest and $\alpha = 0.75$ for the posttest (see Table 2); both values were therefore comparable with the results of the pilot study. According to George and Mallery [74] as well as Cronbach [75], the internal consistency reaches the acceptable level for the posttest.

Table 2. Overview of Psychometric Criteria.

	Internal Consistency (Cronbach's α)	Medium Difficulty (Min. < p Mean < Max.)	Discriminatory Power (Min. < rit Mean < Max.)
Pretest	0.68	0.08 < 0.53 < 0.79	0.01 < 0.24 < 0.43
Posttest	0.75	0.09 < 0.59 < 0.82	0.06 < 0.31 < 0.46

The medium difficulty was 0.08 (Min.), <0.53 (p Mean) and <0.79 (Max.) for the pretest and 0.09 (Min.), <0.59 (p Mean) and <0.82 (Max.) for the posttest (see Table 2). Values between 0.2 and 0.8 are considered acceptable, particularly for the pretest (see [76,77]), to ensure good differentiation of the test even at varying performance levels.

The discriminatory power of individual items was 0.01 (Min.), <0.24 (Median rit) and <0.43 (Max.) in the pretest and 0.06 (Min.), <0.31 (Median rit) and <0.46 (Max.) in the posttest (see Table 2). The discriminatory power of the pretest items was slightly lower than the power of the pilot study items. According to Weise [78], the pretest values were somewhat lower than the recommended discriminatory power minimum of >0.3, whereas the posttest values were somewhat higher. However, Schecker [79] proposed different discriminatory power limits for performance assessment, which were fulfilled both by pre- and posttest.

4.2. Analysis of Independent Variables

We first tested whether test scores correlated with school grades in math, German and NWA (see Table 3). Given that German school grades decrease with increasing quality (1 = excellent and 6 = insufficient), correlation coefficients are negative for performance gains.

Table 3. Correlations of Sex, Native Tongue and School Grades Inside the Test Groups.

	Sex	Native Tongue of Mother	Native Tongue of Father	School Grade German	School Grade Math	School Grade NWA
Pre-EG1	0.109	0.115	0.114	−0.256 *	−0.326 **	−0.327 **
Pre-EG2	0.074	0.076	0.045	0.009	0.095	0.128
Pre-KG	0.015	0.016	0.046	0.048	0.032	0.194
Pos-EG1	0.265 *	0.228	0.176	−0.363 **	−0.357 **	−0.429 **
Pos-EG2	−0.123	−0.188 *	−0.060	0.055	−0.017	−0.052
Pos-KG	−0.019	0.008	0.027	0.184	0.085	0.173

Note. * $p < 0.05$; ** $p < 0.01$. $0.1 \leq$ weak < 0.3; $0.3 \leq$ medium < 0.5; $0.5 \leq$ high correlation [80].

None of the tested independent variables showed a strong correlation with the test results; however, some medium and weak correlations were found. The pretest results of experimental group 1 (EG1) showed a medium correlation with NWA grade (r = −0.33) and math grade (r = −0.33) and a weak correlation with the German grade (r = −0.26). All correlation coefficients increased in the posttest (r = −0.43 NWA grade, r = −0.36 math grade, r = −0.36 German grade). Neither experimental group 2 nor the control group showed any significant correlations.

In addition to school grades, we also tested for correlations with sex and native tongue of each parent. These variables showed only a weak correlation with systems thinking in isolated test groups (see Table 3).

Table 4 shows a correlation analysis of various motivations and attitudes with 11 weak but significant correlations (three in EG1 pretest, eight in EG2 posttest). These results suggest that the investigated motivations and attitudes are basically unrelated to improving systems thinking in school.

Table 4. Correlation Analysis of Various Motivations and Attitudes with NWA.

	In NWA It Is Important for Me:										
	To Understand Course Content	To Work Effortlessly	To Understand Complex Content	Not to Understand Difficult Questions or Solve difficult Tasks	To Make Sense of What I Learned	To Pass the Course with Little Effort	That Work Is Done Easily	To Learn Interesting Things	I Am Better in NWA than My Classmates	I Solve NWA Tasks Easier than My Class-Mates	Learning Something New in NWA Is Easier for Me than for My Classmates
Pre-EG1	0.226	0.199	0.226	0.184	0.226	0.217	0.210	0.222	0.285 *	0.288 *	0.294 *
Pre-EG2	−0.058	−0.050	−0.064	−0.049	−0.059	−0.032	−0.041	−0.054	0.067	0.068	0.067
Pre-KG	0.085	0.099	0.081	0.099	0.077	0.102	0.078	0.087	0.047	0.051	0.054
Pos-EG1	−0.151	−0.195	−0.142	−0.187	−0.153	−0.201	−0.197	−0.170	0.067	0.184	0.073
Pos-EG2	−0.239 *	−0.239 *	−0.237 *	−0.233 *	−0.242 *	−0.246 **	−0.235 *	−0.209 *	−0.060	−0.150	−0.126
Pos-KG	0.070	0.088	0.067	0.075	0.077	0.130	0.098	0.084	0.078	0.057	0.025

Note. * $p < 0.05$; ** $p < 0.01$. $0.1 \leq$ weak < 0.3; $0.3 \leq$ medium < 0.5; $0.5 \leq$ high correlation [80].

NWA, Math and German grades showed medium correlations (see Table 3). Therefore, a covariance analysis was performed with NWA, Math and German grades as covariates. However, only NWA revealed an effect on systems thinking scores (see Figure 6).

Table 5 shows the results of the pre- and posttests. The highest possible score for both tests was 24 points. In the pretest, experimental group 1 (EG1) showed the best results (Pre-EG1: 13.41, SD = 2.31), followed by experimental group 2 (Pre-EG2: 12.87, SD = 2.46) and the control group (Pre-CG: 12.35, SD = 2.53). The minimum and maximum values varied in all groups (Min: 4.50–9.50, Max: 17.48–19.80). Performance of experimental group 1 proved significantly better compared to the control group (see Figure 5). No other significant difference could be shown between any other groups.

Table 5. Results of Pre- and Posttests.

	Mean	SD	Min.	Max.	N
Pre-EG1	13.41	2.31	9.50	19.80	70
Pre-EG2	12.87	2.46	4.50	17.48	111
Pre-CG	12.35	2.53	6.67	17.83	108
Post-EG1	14.98	2.51	7.67	20.55	70
Post-EG2	14.59	2.61	5.58	19.42	111
Post-CG	13.35	2.68	7.42	19.92	108

Note. Maximum score = 24 points.

The posttest performance of all groups increased, but the group ranking did not change. The best performance was found in experimental group 1 (14.98, SD = 2.51) followed by experimental group 2 (14.59, SD = 2.61) and finally the control group. The pretest minimum and maximum values varied in all groups (Min: 5.58–7.67, Max: 19.42–20.55).

All groups, including the control group, showed a highly significant performance increase in the posttest (see Figure 5).

To compensate for the unexpected 4% increase in the control group's performance, we calculated the net effect based on Rosi and Freeman ([81], p. 238). Figure 6 shows the results of the compensated performance changes. The net increases were 0.57 points (2.4%) for experimental group 1, 0.73 points (3.0%) for experimental group 2 and 0 for the control group.

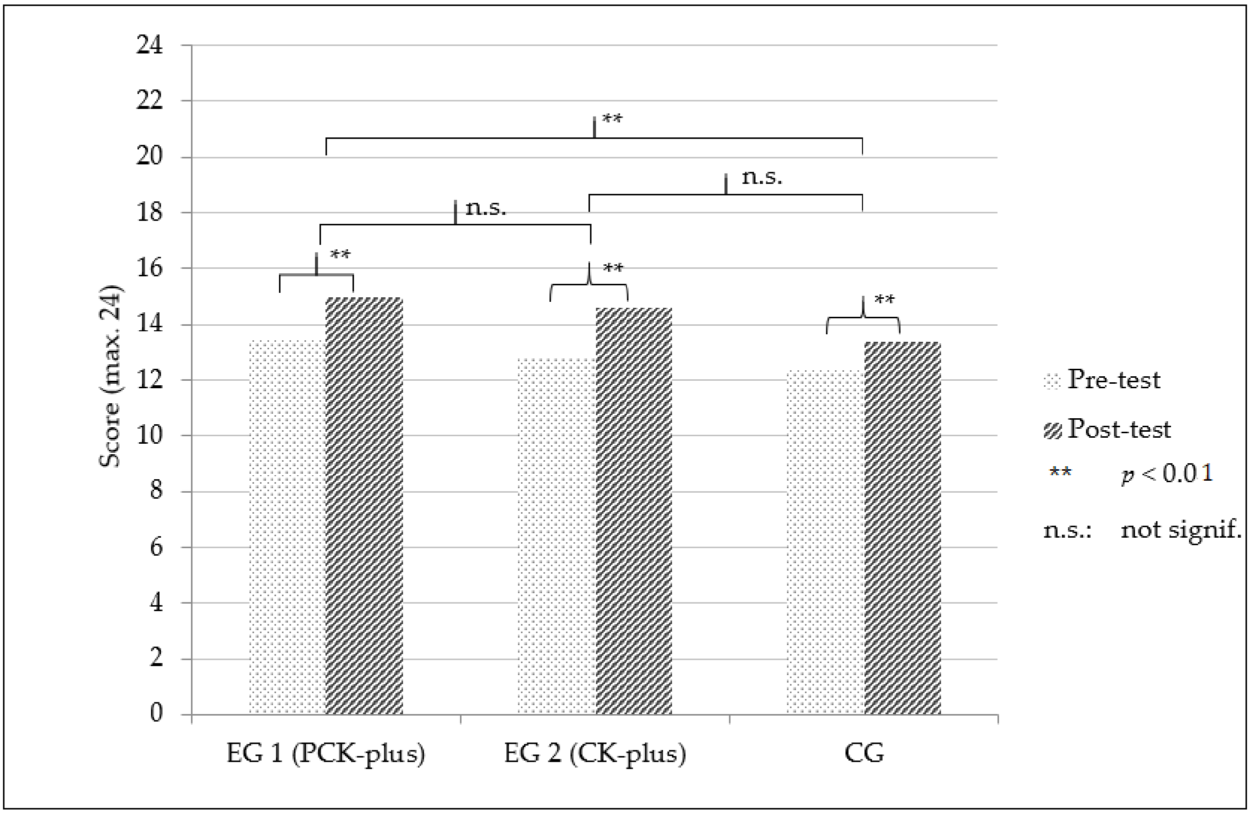

Figure 5. Overall results (24 Items).

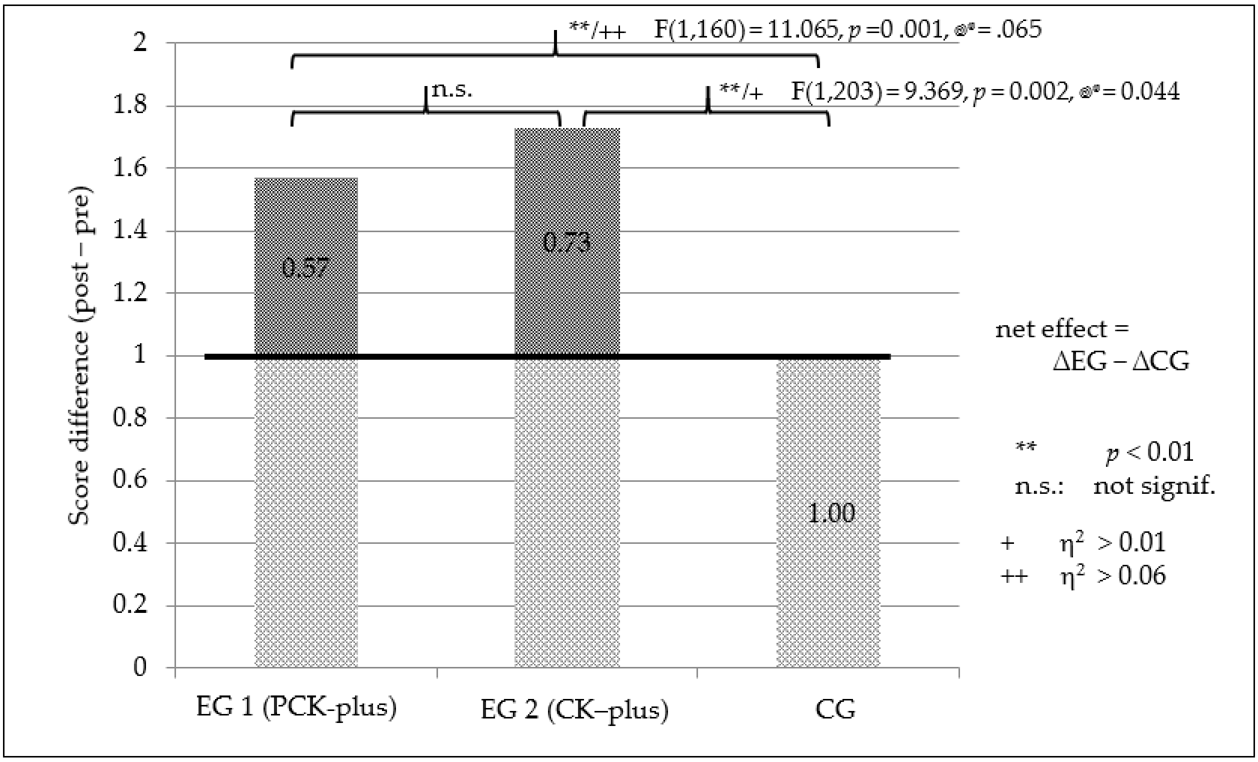

Figure 6. Net effects and effect sizes of teacher training in systems thinking on students (dimensions 1–3 combined). The net effects and effect sizes of each individual dimension were also calculated but the results were identical.

To calculate significance tests and effect sizes between groups, a covariance analysis was performed with pretest score and NWA grade as covariates [82]. This procedure reduces the unwanted effects of the pretest baseline shift (EG1 to CG), posttest improvement (CG) and NWA scores on experimental group 1 (see Table 3).

This analysis showed that experimental group 1 and 2 had a highly significant posttest performance increase compared to the pretest (see Figure 6). No significant difference was found between both experimental groups. However, the performance increase compared to the control group is significant for both experimental groups (see Figure 6). Effect sizes defined by Cohen ([80], p. 283 et seq.) were medium for experimental group 1 (F(1160) = 11.07, p = 0.001, η^2 = 0.07) and weak for experimental group 2 (F(1203) = 9.40, p = 0.002, η^2 = 0.04).

The same analysis was used to investigate the competence model in which subgroups of items belonging to a specific dimension could be analyzed and compared. The results showed a significant increase in all three incorporated dimensions (1. Declarative/Conceptual systems knowledge, 2. Modeling systems and 3. Solving problems). The effect sizes of individual dimensions were similar to the sizes of the overall results (see Figure 6).

5. Discussion and Conclusions

Our results show that systems thinking performance of biology students can be promoted successfully by training in-service biology teachers, which supports our first hypothesis. To our knowledge no other studies could successfully show this effect. Only few studies have investigated the effects of teacher training in natural science at the student performance level [57,83,84]. In contrast to the weak effect size in these studies, we could obtain a medium effect size with one of our experimental groups on student performance. This result is particularly notable as the training program consisted of only 28 lessons (corresponds to 28 h) spread over 4 days. Increased intervention duration is expected to provide even higher effect sizes as reported in several studies that showed a relation between intervention duration and effectiveness [62,85–87]. Yoon et al. [62] conducted a meta-study of 1300 publications, showing that the minimum intervention duration for successful teacher training is 30 lessons. However, intervention duration on its own is no measure of intervention quality [88,89].

Our second question addressed the extent that PCK content affects the performance of the biology students. Our results indicate that a minor increase of PCK (EG1:16 h PCK vs. 12h CK; EG2: 20 h CK vs. 8 h PCK) resulted in a prominent increase in effect sizes. These results correspond with current findings of al. [26,28,34,58], who conducted similar studies to develop preservice and in-service biology teachers’ professional knowledge in teaching systems thinking. Comparable results could also be found in the related fields of mathematics and natural sciences by [49–51,90]. These findings are consistent with fundamental theoretical considerations of [41,52,91,92], which particularly emphasize the relevance of PCK for successful professional teaching [59]. Nevertheless, many studies have emphasized the basic importance of CK [93–95]. Hence, our thinking is consistent with [48,53,91] who argued that a basic level of CK is needed to successfully train learners in PCK. Noteworthy is the main difference between experimental group 1 (PCK-plus) and experimental group 2 (CK-Plus). After scrutinizing the data for intervention day 4, the inclusion of this trial and the reflection phases on this day in group 1 was the key to successful performance increases. By providing ideas and not finished teaching concepts and also their subsequent reflection, teachers should be encouraged to own activity. This is based on the self-determination theory of Deci and Ryan [68], which predicts a higher motivation for self-directed and self-organized learning. In accordance with [63,64,96], these phases proved very important for successful teacher trainings.

Finally, we would like to address some weaknesses of this study and thus starting points for subsequent studies. Among other points, the varying base levels of the experimental groups and the control group (see Figures 5 and 6) had an unfavorable effect on the data analysis. This effect could have been influenced by the fact that the students remained in their class structures, which were groups that had naturally evolved instead of being randomly selected. Borz & Döring ([97], p. 555 et seq.) characterized this shortcoming as a typical problem of the quasi-experimental approach. To counterbalance this effect, we increased randomization by randomly distributing the 15 classes to the three groups. Nevertheless, we found a significant base level variation between experimental group 1 and the control group in the pretest results. To compensate this undesired effect, we identified two covariates (pretest score and NWA grade) and included them into a covariance analysis (see Figure 6), which is an appropriate procedure to minimize effects of insufficient randomization [97].

Furthermore, assessing long-term effects was not possible. The posttest in the current study was performed approximately two weeks after the intervention. Future studies could incorporate a follow-up design to investigate the long-term impact of the observed effects. In addition, it would be desirable in an interdisciplinary study, together with general education sciences, to clarify the influence of PK to foster systems thinking in students. As the use of computer simulations can specifically promote the teaching of systems thinking [5,30,31], it would be valuable to investigate what roles Technological Knowledge (TK) and Technological Pedagogical Content Knowledge (TPACK) play in this context. Technological Knowledge (TK) is a more recent extension of the concepts of CK and PK. The combination of the three concepts results in the Technological Pedagogical Content Knowledge (TPACK), which "has been introduced as a conceptual framework for the knowledge base teachers need to effectively teach with technology" ([98], p. 109).

Supplementary Materials: The following document is available online at https://www.mdpi.com/article/10.3390/su13147631/s1, S1: Questionnaire in original language (German).

Author Contributions: Conceptualization, S.S. and W.R.; methodology, S.S.; software, S.S.; validation, S.S. and W.R.; investigation, S.S.; resources, S.S. and W.R.; data curation, S.S.; writing—original draft preparation, S.S.; writing—review and editing, S.S., W.R. and C.H.; supervision, W.R.; project administration, S.S.; funding acquisition, S.S. and W.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science, Research and Culture of Baden-Wuerttemberg and the KeBU (Competence Network of empirical Education and Teaching research) by the University of Education Freiburg and the University of Freiburg. The article processing charge (APC) was funded by the Baden-Wuerttemberg Ministry of Science, Research and Culture and the University of Education Freiburg in the funding program Open Access Publishing.

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

Data Availability Statement: Additional data are available from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. McLellan, R.; Grooten, M.; Almond, R. *Living Planet Report 2012: Biodiversity, Biocapacity and Better Choices*; World Wide Fund For Nature (WWF): Gland, Switzerland, 2012; ISBN 978-2-940443-37-6.
2. Nations Conference on Environment & Development Rio de Janeiro, Brazil, 3–14 June 1992: Agenda 21. Rio de Janeiro, Brazil, 1992. Available online: https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf (accessed on 5 March 2021).
3. Assaraf, O.B.-Z.; Orpaz, I. The "Life at the Poles" Study Unit: Developing Junior High School Students' Ability to Recognize the Relations Between Earth Systems. *Res. Sci. Educ.* **2010**, *40*, 525–549. [CrossRef]
4. Bertschy, F. Vernetztes Denken in der Grundschule fördern. *Umweltpsychologie* **2008**, *12*, 71–90.
5. Riess, W.; Mischo, C. Promoting Systems Thinking through Biology Lessons. *Int. J. Sci. Educ.* **2010**, *32*, 705–725. [CrossRef]
6. Wals, A.E.J. Shaping the education of tomorrow: 2012 full-length report on the UN Decade for Education for Sustainable Development. In *United Nations Decade of Education for Sustainable Development (2005–2014)*; United Nations Educational, Scientific and Cultural Organization (UNESCO): Paris, France, 2012.
7. Boersma, K.; Waarlo, A.J.; Klaassen, K. The feasibility of systems thinking in biology education. *J. Biol. Educ.* **2011**, *45*, 190–197. [CrossRef]

8. Jacobson, M.J.; Wilensky, U. Complex systems in education: Scientific and educational importance and implications for the learning sciences. *J. Learn. Sci.* **2006**, *15*, 11–34. [CrossRef]
9. Manderson, A.K. A Systems Based Framework to Examine The Multi-contextural Application of the Sustainability Concept. *Environ. Dev. Sustain.* **2006**, *8*, 85–97. [CrossRef]
10. Eilam, B. System thinking and feeding relations: Learning with a live ecosystem model. *Instr. Sci.* **2012**, *40*, 213–239. [CrossRef]
11. Jacobson, M.J. Problem solving, cognition, and complex systems: Differences between experts and novices. *Complexity* **2001**, *6*, 41–49. [CrossRef]
12. Von Bertalanffy, L. *General System Theory: Foundations, Development, Applications*; Braziller: New York, NY, USA, 1968.
13. Bossel, H. *Systems and Models: Complexity, Dynamics, Evolution, Sustainability*; Books on Demand GmbH: Norderstedt, Germany, 2007; ISBN 9783833481215.
14. Biber, P.; Kasperidus, H.D. Integrated Modeling Approaches and System Dynamics in Education Related to Sustainable Resource Management, Forestry, and Land use Management. In Proceedings of the 22nd System Dynamics Conference, Oxford, UK, 25–29 July 2004; Kennedy, M., Winch, G.W., Langer, R.S., Rowe, J.I., Yanni, J.M., Eds.; System Dynamics Society: Littleton, MA, USA, 2004; p. 43. Available online: https://proceedings.systemdynamics.org/2004/SDS_2004/PROCEED.pdf (accessed on 6 July 2021).
15. Sweeney, L.B.; Sterman, J.D. Bathtub dynamics: Initial results of a systems thinking inventory. *Syst. Dyn. Rev.* **2000**, *16*, 249–286. [CrossRef]
16. Schurz, J. *Systemdenken in der Naturwissenschaft*; Carl-Auer: Heidelberg, Germany, 2006; ISBN 3896703641.
17. Ossimitz, G. *Entwicklung Systemischen Denkens: Theoretische Konzepte und Empirische Untersuchungen*; Profil-Verl.: München, Germany, 2000; ISBN 9783890194943.
18. Bollmann-Zuberbühler, B. *Systemisches Denken an der Sekundarstufe I: Eine Interventionsstudie: Abhandlung*; Universität Zürich: Zürich, Switzerland, 2010.
19. Sommer, C.; Lücken, M. System Competence—Are elementary students able to deal with a biological system? *NorDiNa* **2010**, *6*, 125–143. [CrossRef]
20. Rempfler, A.; Uphues, R. System Competence in Geography Education: Development of Competence Models, Diagnosing Pupils´ Achievement. *Eur. J. Geogr.* **2012**, *3*, 6–22.
21. Rates, C.A.; Mulvey, B.K.; Feldon, D.F. Promoting conceptual change for complex systems understanding: Outcomes of an agent-based participatory simulation. *J. Sci. Educ. Technol.* **2016**, *25*, 610–627. [CrossRef]
22. Mehren, R.; Rempfler, A.; Buchholz, J.; Hartig, J.; Ulrich-Riedhammer, E.M. System competence modelling: Theoretical foundation and empirical validation of a model involving natural, social and human-environment systems. *J. Res. Sci. Teach.* **2018**, *55*, 685–711. [CrossRef]
23. Brockmüller, S.; Siegmund, A. Erfassung und Entwicklung von Systemkompetenz–Empirische Befunde zu Kompetenzstruktur und Förderbarkeit durch den Einsatz analoger und digitaler Modelle. *Z. Geogr. ZGD* **2020**, *48*, 31–49. [CrossRef]
24. Ossimitz, G. Stock-flow thinking and reading stock-flow-related graphs: An empirical investigation in dynamics thinking abilities. In *Stock-Flow-Thinking and Reading Stock-Flow-Related Graphs: An Empirical Investigation in Dynamic Thinking Abilities, Proceedings of the 2002 International System Dynamics Conference, Palermo, 28 July–1 August 2002*; System Dynamics Society: Albany, NY, USA, 2002.
25. Bräutigam, J.I. Systemisches Denken im Kontext Einer Bildung für nachhaltige Entwicklung: Konstruktion und Validierung eines Messinstruments zur Evaluation Eriner Unterrichtseinheit. Dissertation. Available online: http://nbn-resolving.de/urn:nbn:de:bsz:frei129-opus-4387 (accessed on 2 January 2021).
26. Fanta, D.; Braeutigam, J.; Riess, W. Fostering systems thinking in student teachers of biology and geography—An intervention study. *J. Biol. Educ.* **2019**, *54*, 226–244. [CrossRef]
27. Fraune, K. Modeling System Thinking—Assessment, Structure Validation and Development. Ph.D. Thesis, Christian-Albrechts-University Kiel, Kiel, Germany, 2014.
28. Rosenkränzer, F.; Hörsch, C.; Schuler, S.; Riess, W. Student teachers' pedagogical content knowledge for teaching systems thinking: Effects of different interventions. *Int. J. Sci. Educ.* **2017**, *39*, 1932–1951. [CrossRef]
29. Schuler, S.; Fanta, D.; Rosenkraenzer, F.; Riess, W. Systems thinking within the scope of education for sustainable development (ESD)—A heuristic competence model as a basis for (science) teacher education. *J. Geogr. High. Educ.* **2018**, *42*, 192–204. [CrossRef]
30. Dörner, D. *The Logic of Failure: Recognizing and Avoiding Error in Complex Situations*; Basic Books: New York, NY, USA, 1996; ISBN 0201479486.
31. Leutner, D.; Schrettenbrunner, H. Entdeckendes Lernen in komplexen Realitaetsbereichen: Evaluation des Computer-Simulationsspiels: "Hunger in Nordafrika". *Unterrichtswissenschaft* **1989**, *17*, 327–341.
32. Maierhofer, M. *Förderung des Systemischen Denkens Durch Computerunterstützten Biologieunterricht*; GCA: Herdecke, Germany, 2001; ISBN 3898630633.
33. Assaraf, O.B.-Z.; Dodick, J.; Tripto, J. High school students' understanding of the human body system. *Res. Sci. Educ.* **2013**, *43*, 33–56. [CrossRef]
34. Fanta, D.; Bräutigam, J.; Greiff, S.; Rieß, W. Entwicklung und Validierung eines Messinstrumentes zur Erfassung von systemischem Denken bei Lehramtsstudierenden in ökologischen Kontexten. *Z. Didakt. Naturwiss.* **2017**, *23*, 241–259. [CrossRef]

35. Hattie, J. *Visible Learning: A Synthesis of over 800 Meta-Analyses Relating to Achievement*; Routledge: London, UK, 2009; ISBN 9786611901288.
36. Abell, S.K. Research on science teacher knowledge. In *Handbook of Research on Science Education*, 1st ed.; Abell, S.K., Lederman, N.G., Eds.; Lawrence Erlbaum: Mahwah, NJ, USA, 2007; pp. 1105–1149; ISBN 9780805847130.
37. Cronin, M.A.; Gonzalez, C.; Sterman, J.D. Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. *Organ. Behav. Hum. Decis. Process.* **2009**, *108*, 116–130. [CrossRef]
38. Rieß, W.; Schuler, S.; Hörsch, C. Wie lässt sich systemisches Denken vermitteln und fördern? Theoretische Grundlagen und praktische Umsetzung am Beispiel eines Seminars für Lehramtsstudierende. *Geogr. Aktuell Sch.* **2015**, *37*, 16–29.
39. Cochran-Smith, M.; Zeichner, K.M. *Studying Teacher Education: The Report of the AERA Panel on Research and Teacher Education*; Lawrence Erlbaum Associates: Mahwah, NJ, USA, 2005; ISBN 1135184402.
40. Rivkin, S.G.; Hanushek, E.A.; Kain, J.F. Teachers, schools, and academic achievement. *Econometrica* **2005**, *73*, 417–458. [CrossRef]
41. Shulman, L.S. Those Who Understand: Knowledge Growth in Teaching. *Educ. Res.* **1986**, *15*, 4–14. [CrossRef]
42. Hashweh, M.Z. Effects of subject-matter knowledge in the teaching of biology and physics. *Teach. Teach. Educ.* **1987**, *3*, 109–120. [CrossRef]
43. Tenorth, H.-E. Professionalität im Lehrerberuf. *Z. Erziehungswiss.* **2006**, *9*, 580–597. [CrossRef]
44. Ständige Konferenz der Kultusminister der Länder in der Bundesrepublik Deutschland (KMK). Ländergemeinsame Inhaltliche Anforderungen für die Fachwissenschaften und Fachdidaktiken in der Lehrerbildung. 2008. Available online: https://www.kmk.org/fileadmin/veroeffentlichungen_beschluesse/2008/2008_10_16-Fachprofile-Lehrerbildung.pdf (accessed on 2 February 2021).
45. Morrell, P.; Park Rogers, M.; Pyle, E.; Roehrig, G.; Veal, W. 2020 NSTA/ASTE Standards for Science Teacher Preparation. Available online: https://static.nsta.org/pdfs/2020NSTAStandards.pdf (accessed on 10 March 2021).
46. Borko, H.; Putnam, R.T. Learning to teach. In *Handbook of Educational Psychology*; Berliner, D.C., Calfee, R.C., Eds.; Routledge: London, UK, 1996; pp. 673–708; ISBN 0805850805.
47. Borowski, A.; Carlson, J.; Fischer, H.E.; Henze, I.; Gess-Newsome, J.; Kirschner, S.; van Driel, J.H. Different models and methods to measure teachers' pedagogical content knowledge. In *Science Learning and Citizenship, E-book Proceedings of the ESERA 2011 Conference, Lyon, France, 5-9 September 2011*; Bruguière, C., Tiberghien, A., Clément, P., Eds.; European Science Education Research Association: Utrecht, The Netherlands, 2012; pp. 37–40; ISBN 978-9963-700-44-8.
48. Krauss, S.; Baumert, J.; Blum, W. Secondary mathematics teachers' pedagogical content knowledge and content knowledge: Validation of the COACTIV constructs. *ZDM Math. Educ.* **2008**, *40*, 873–892. [CrossRef]
49. Kunter, M.; Baumert, J. The COACTIV research program on teachers' professional competence: Summary and discussion. In *Cognitive Activation in the Mathematics Classroom and Professional Competence of Teachers*; Kunter, M., Baumert, J., Blum, W., Klusmann, U., Krauss, S., Neubrand, M., Eds.; Springer: New York, NY, USA, 2013; pp. 345–368; ISBN 978-1-4614-5149-5.
50. Lange, K.; Ohle, A.; Kleickmann, T.; Kauertz, A.; Möller, K.; Fischer, H.E. Zur Bedeutung von Fachwissen und fachdidaktischem Wissen für Lernfortschritte von Grundschülerinnen und Grundschülern im naturwissenschaftlichen Sachunterricht. *Z. Grundschul.* **2015**, *8*, 23–38.
51. Sadler, P.M.; Sonnert, G.; Coyle, H.P.; Cook-Smith, N.; Miller, J.L. The influence of teachers' knowledge on student learning in middle school physical science classrooms. *Am. Educ. Res. J.* **2013**, *50*, 1020–1049. [CrossRef]
52. Borko, H. Professional development and teacher learning: Mapping the terrain. *Educ. Res.* **2004**, *33*, 3–15. [CrossRef]
53. Grossschedl, J.; Mahler, D.; Kleickmann, T.; Harms, U. Content-related knowledge of biology teachers from secondary schools: Structure and learning opportunities. *Int. J. Sci. Educ.* **2014**, *36*, 2335–2366. [CrossRef]
54. Park, S.; Oliver, J.S. Revisiting the Conceptualisation of Pedagogical Content Knowledge (PCK): PCK as a Conceptual Tool to Understand Teachers as Professionals. *Res. Sci. Educ.* **2008**, *38*, 261–284. [CrossRef]
55. Gess-Newsome, J. Pedagogical content knowledge: An introduction and orientation. In *Examining Pedagogical Content Knowledge*; Gess-Newsome, J., Lederman, N.G., Eds.; Springer: Dordrecht, The Netherlands, 1999; pp. 3–17.
56. Munby, H.; Russell, T.; Martin, A.K. Teachers' knowledge and how it develops. In *Handbook of Research on Teaching*; Richardson, V., Ed.; Macmillan: New York, NY, USA, 2001; pp. 877–904; ISBN 0935302263.
57. Lipowsky, F. Theoretische Perspektiven und empirische Befunde zur Wirksamkeit von Lehrerfort-und-weiterbildung. In *Handbuch der Forschung zum Lehrerberuf*; Terhart, E., Bennewitz, H., Rothland, H., Eds.; Waxmann: Münster, Germany, 2011; pp. 398–417; ISBN 3830930755.
58. Mahler, D.; Großschedl, J.; Harms, U. Using doubly latent multilevel analysis to elucidate relationships between science teachers' professional knowledge and students' performance. *Int. J. Sci. Educ.* **2017**, *39*, 213–237. [CrossRef]
59. Lipowsky, F.; Rzejak, D. Lehrerinnen und Lehrer als Lerner-Wann gelingt der Rollentausch? Merkmale und Wirkungen wirksamer Lehrerfortbildungen. *Reform Lehrerbild. Deutschl. Österreich Schweiz* **2012**, *1*, 235–253.
60. Gräsel, C.; Fußangel, K.; Pröbstel, C. Lehrkräfte zur Kooperation anregen-eine Aufgabe für Sisyphos? *Z. Pädagog.* **2006**, *52*, 205–219.
61. Smith, C.; Gillespie, M. Research on professional development and teacher change: Implications for adult basic education. *Rev. Adult Learn. Lit.* **2007**, *7*, 205–244.
62. Yoon, K.S.; Duncan, T.; Lee, S.W.-Y.; Scarloss, B.; Shapley, K.L. Reviewing the evidence on how teacher professional development affects student achievement. In *Issues & Answers*; Institute of Education Sciences, U.S. Department of Education: Washington, DC, USA, 2007.

63. Garet, M.S.; Cronen, S.; Eaton, M.; Kurki, A.; Ludwig, M.; Jones, W.; Uekawa, K.; Falk, A.; Bloom, H.S.; Doolittle, F. *The Impact of Two Professional Development Interventions on Early Reading Instruction and Achievement. NCEE 2008-4030*; National Center for Education Evaluation and Regional Assistance: Washington, DC, USA, 2008.
64. Neuman, S.B.; Cunningham, L. The impact of professional development and coaching on early language and literacy instructional practices. *Am. Educ. Res. J.* **2009**, *46*, 532–566. [CrossRef]
65. Reusser, K. Problemorientiertes Lernen.–Tiefenstruktur, Gestaltungsformen, Wirkung. *Beitr. Lehr. Lehrerbild.* **2005**, *23*, 159–182.
66. Gräsel, C.; Parchmann, I.; Puhl, T.; Baer, A.; Fey, A.; Demuth, R. Lehrerfortbildung und ihre Wirkungen auf die Zusammenarbeit von Lehrkräften und die Unterrichtsqualität. In *Bildungsqualtiät von SchuleUnterrichtsqualität*; Doll, J., Prenzel, M., Eds.; Waxmann: Münster, Germany, 2004; pp. 136–137.
67. Gräsel, C.; Fußangel, K.; Schellenbach-Zell, J. Transfer einer Unterrichtsinnovation: Das Beispiel Chemie im Kontext. In *Pädagogische Professionalität als Gegenstand Empirischer Forschung*; Waxmann: Münster, Germany, 2008; pp. 207–218; ISBN 9783830920342.
68. Deci, E.L.; Ryan, R.M. *Intrinsic Motivation and Self-Determination in Human Behavior*; Plenum Press: New York, NY, USA, 1985; ISBN 0306420228.
69. Matthies, M.; Pfäfflin, F.; Berlekamp, J. GIS-Based Catchment Modeling. In *Integrative Systems Approaches to Natural and Social Dynamics: Systems Science 2000*; Matthies, M., Allen, P.M., Kriz, J., Eds.; Springer: Berlin, Germany, 2001; pp. 171–180; ISBN 3540412921.
70. Bollmann-Zuberbühler, B. *Systemdenken Fördern: Systemtraining und Unterrichtsreihen zum Vernetzten Denken; 1.—9. Schuljahr; Impulse zur Unterrichtsentwicklung*, 1st ed.; Schulverl. Plus: Bern, Switzerland, 2010; ISBN 9783292006288.
71. Hussy, W.; Schreier, M.; Echterhoff, G. *Forschungsmethoden in Psychologie und Sozialwissenschaften für Bachelor*, 2nd ed.; Springer: Berlin, Germany, 2013; ISBN 9783642343629.
72. Schöne, C.; Dickhäuser, O.; Spinath, B.; Stiensmeier-Pelster, J. *Skalen zur Erfassung des schulischen Selbstkonzepts: SESSKO*; Hogrefe: Göttingen, Germany, 2012.
73. Spinath, B.; Stiensmeier-Pelster, J.; Schöne, C.; Dickhäuser, O. *Skalen zur Erfassung der Lern-und Leistungsmotivation: SELLMO*; Hogrefe: Göttingen, Germany, 2002.
74. Geroge, D.; Mallery, P. *SPSS for Windows Step by Step: A Simple Guide and Reference*; Allyn & Bacon: Boston, MA, USA, 2003.
75. Cronbach, L.J. Coefficient alpha and the internal structure of tests. *Psychometrika* **1951**, *16*, 297–334. [CrossRef]
76. Bühner, M. *Einführung in die Test- und Fragebogenkonstruktion*, 3rd ed.; Pearson Studium: München, Germany, 2011; ISBN 1283736403.
77. Lienert, G.A.; Raatz, U. *Testaufbau und Testanalyse*; Beltz: Weinheim, Germany, 1998; ISBN 3621274243.
78. Weise, G. *Psychologische Leistungstests: Ein Handbuch für Studium und Praxis. Band 1: Intelligenz—Konzentration—Spezielle Fähigkeiten*; Hogrefe Verlag: Göttingen, Germany, 1975; ISBN 9783801701017.
79. Schecker, H. Überprüfung der Konsistenz von Itemgruppen mit Cronbachs α. In *Methoden in der Naturwissenschaftsdidaktischen Forschung*; Krüger, D., Parchmann, I., Schecker, H., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 1–15. ISBN 978-3-642-37827-3.
80. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Lawrence Erlbaum Associates: Hillsdale, NJ, USA, 1988; ISBN 1299626793.
81. Rossi, P.H.; Freeman, H.E.; Wright, S.R. *Evaluation: A Systematic Approach*; Sage: Beverly Hills, CA, USA, 1985; ISBN 9780761908944.
82. Dugard, P.; Todman, J. Analysis of pre-test-post-test control group designs in educational research. *Educ. Psychol.* **1995**, *15*, 181–198. [CrossRef]
83. Fischler, H. Theory and practice in science teacher education: The German Experience. In *Professional Development of Science Teachers*; Fraser-Abder, P., Ed.; Routledge: London, UK, 2002; pp. 100–114.
84. Wackermann, R.; Trendel, G.; Fischer, H.E. Evaluation of a Theory of Instructional Sequences for Physics Instruction. *Int. J. Sci. Educ.* **2010**, *32*, 963–985. [CrossRef]
85. Garet, M.S.; Porter, A.C.; Desimone, L.; Birman, B.F.; Yoon, K.S. What makes professional development effective? Results from a national sample of teachers. *Am. Educ. Res. J.* **2001**, *38*, 915–945. [CrossRef]
86. Gersten, R.; Dimino, J.; Jayanthi, M.; Kim, J.S.; Santoro, L.E. Teacher study group: Impact of the professional development model on reading instruction and student outcomes in first grade classrooms. *Am. Educ. Res. J.* **2010**, *47*, 694–739. [CrossRef]
87. Penuel, W.R.; Fishman, B.J.; Yamaguchi, R.; Gallagher, L.P. What makes professional development effective? Strategies that foster curriculum implementation. *Am. Educ. Res. J.* **2007**, *44*, 921–958. [CrossRef]
88. Kennedy, M. *Form and Substance in Inservice Teacher Education: Research Monograph 13*; University of Wisconsin, National Institute for Science Education: Madison, WI, USA, 1998.
89. Timperley, H.; Wilson, A.; Barrar, H.; Fung, I. *Teacher Professional Learning and Development: Best Evidence Synthesis Iteration (BES)*; Ministry of Education: Wellington, New Zealand, 2007; ISBN 0790326280.
90. Baumert, J.; Kunter, M.; Blum, W.; Brunner, M.; Voss, T.; Jordan, A.; Klusmann, U.; Krauss, S.; Neubrand, M.; Tsai, Y.-M. Teachers' Mathematical Knowledge, Cognitive Activation in the Classroom, and Student Progress. *Am. Educ. Res. J.* **2010**, *47*, 133–180. [CrossRef]
91. Magnusson, S.; Krajcik, J.; Borko, H. Nature, sources, and development of pedagogical content knowledge for science teaching. In *Examining Pedagogical Content Knowledge: The Construct and Its Implications for Science Education*; Gess-Newsome, J., Lederman, N.G., Eds.; Springer: Dordrecht, The Netherlands, 1999; pp. 95–132.

92. Ball, D.L.; Lubienski, S.T.; Mewborn, D.S. Research on teaching mathematics. The unsolved problem of teachers' mathematical knowledge. In *Handbook of Research on Teaching*; Richardson, V., Ed.; Macmillan: New York, NY, USA, 2001; pp. 433–456; ISBN 0935302263.
93. Hill, H.C.; Rowan, B.; Ball, D.L. Effects of teachers' mathematical knowledge for teaching on student achievement. *Am. Educ. Res. J.* **2005**, *42*, 371–406. [CrossRef]
94. Ohle, A.; Fischer, H.E.; Kauertz, A. Der Einfluss des physikalischen Fachwissens von Primarstufenlehrkräften auf Unterrichtsgestaltung und Schülerleistung. *Z. Didakt. Naturwiss.* **2011**, *17*, 357–389.
95. Rowan, B.; Chiang, F.-S.; Miller, R.J. Using research on employees' performance to study the effects of teachers on students' achievement. *Sociol. Educ.* **1997**, 256–284. [CrossRef]
96. Ball, D.L.; Cohen, D.K. Developing practice, developing practitioners: Toward a practice-based theory of professional education. In *Teaching as the Learning Profession: Handbook of Policy and Practice: Jossey-Bass Education Series*; Darling-Hammond, L., Sykes, G., Eds.; Jossey-Bass: San Francisco, CA, USA, 1999; pp. 3–32; ISBN 078794341X.
97. Bortz, J.; Döring, N. *Forschungsmethoden und Evaluation: Für Human- und Sozialwissenschaftler*, 4th ed.; Springer: Berlin, Germany, 2006; ISBN 9783540333067.
98. Voogt, J.; Fisser, P.; Pareja Roblin, N.; Tondeur, J.; van Braak, J. Technological pedagogical content knowledge—A review of the literature. *J. Comput. Assist. Learn.* **2013**, *29*, 109–121. [CrossRef]