Moving Teaching Away from Transmitting Facts to Co-Constructing Conceptual Understandings: A Cognitively Activating Instructional Approach

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Summary

The recent science education reforms in Germany have stressed that biology teaching should move away from transmitting isolated facts to engaging students in co-constructing interconnected and conceptual level knowledge. It is known that cognitively activating instruction can warrant a deep level engagement with the subject matter. Cognitively activating instruction includes three key dimensions: teaching interconnected and complex subject matter knowledge, use of challenging tasks, and a thoughtful-constructive discourse. There is evidence that cognitively activating instruction can enhance students' cognitive as well as affective outcomes. However, the research in this field has primarily relied on multi-dimensional rating manuals to measure the overall cognitive potential of the lessons. It remains to be investigated how the individual dimensions of this construct affect student outcomes. It also remains unclear how teachers could include the three dimensions of cognitively activating instruction in their regular lessons.

Within the scope of this doctoral work, we addressed these research gaps by focusing on the following three research objectives: 1) describing German biology lessons based on two of the three key dimensions of cognitively activating instruction: teachers' use of challenging tasks and teachers' use of focus questions to initiate and direct thoughtful discourse; 2) ascertaining the influence of these teaching features on students' topic-related knowledge structure; and 3) proposing a lesson-design model that supports teachers in planning and implementing cognitively activating biology lessons.

A pre-selected sample of 30 out of 47 biology lessons (45 minutes each) on the common theme of 'blood and circulatory system, from a previous quasi-experimental pre-post study were re-analyzed in this doctoral study. Additionally, we collaborated with one 11th-grade biology teacher to demonstrate how the explanation oriented teaching approach could be used to plan cognitively activating biology lessons. A descriptive analysis of biology lessons revealed that teachers mostly used lower cognitive level and lower content complexity tasks to orchestrate content-related interactions. This analysis also revealed that very few teachers used focus questions to highlight the purpose of the lesson; moreover, even fewer teachers used explanation-oriented specific and challenging focus questions to orchestrate meaning-making discussions.

A multilevel analysis depicted a small magnitude positive effect of high-level cognitive processing tasks on students' topic-related knowledge structure; however, we did not find any

effect of higher content complexity tasks on this outcome variable. Furthermore, while the teachers' use of specific and challenging focus questions predicted students' topic-related knowledge structure, there was no significant effect of teachers' use of non-specific or simple focus questions on the outcome variable. Additionally, the collaborative lesson-design work with the grade 11 biology teacher demonstrated how the scientific practice of constructing explanations could be used as a vehicle to plan and implement cognitively activating biology lessons.

In conclusion, while the descriptive findings revealed that the teacher-centered, fact-driven instructional practices were prominent in German biology lessons, the correlational findings demonstrated a small magnitude positive effect of cognitively activating instructional features on students' knowledge structure. Additionally, the explanation-oriented teaching model provided insights into planning cognitive activating biology lessons. Overall, the results obtained from this doctoral thesis advocate the use of cognitively activating instructional model in regular biology teaching in order to reform biology education.

Zusammenfassung

Die jüngsten wissenschaftlichen Bildungsreformen in Deutschland fordern, dass der Schwerpunkt naturwissenschaftlichen Unterrichts nicht mehr auf der Vermittlung isolierter Fakten liegt, sondern darin ko-konstruktiv vernetztes und konzeptuelles Wissen beim Schüler aufzubauen. Hierzu eignet sich kognitiv aktivierender Unterricht, da dabei eine tiefe Auseinandersetzung mit einem fachlichen Inhalt möglich ist. Kognitiv aktivierender Unterricht umfasst drei Schlüssel-Dimensionen: Unterrichten von miteinander vernetztem und komplexem Fachwissen, die Verwendung anspruchsvoller Aufgaben und das Führen eines nachdenklich-konstruktiven Diskurses. Es gibt Hinweise darauf, dass kognitiv-aktivierender Unterricht sowohl die kognitiven als auch affektiven Lernergebnisse der Schülerinnen und Schüler verbessert. Allerdings beruht die Forschung in diesem Bereich in erster Linie auf mehrdimensionalen Rating Manualen, anhand derer das gesamte kognitive Potential der Stunde bemessen wird. Es bleibt noch zu untersuchen, wie die einzelnen Dimensionen des Konstruktes die Schülerleistungen beeinflussen. Zudem ist noch unklar wie Lehrkräfte die drei Dimensionen des kognitiv aktivierenden Unterrichts in ihren gewöhnlichen Unterricht integrieren können.

Im Rahmen dieser Doktorarbeit wurde versucht, diese Forschungslücken anzugehen, indem die folgenden drei Hauptforschungsziele im Fokus der Untersuchung standen: 1) die Beschreibung deutscher Biologiestunden in Bezug auf zwei der drei Dimensionen des kognitiv aktivierenden Unterrichts: die Verwendung von anspruchsvollen Aufgaben und die Verwendung von Schwerpunktfragen durch die Lehrkräfte, um nachdenkliche Diskurse zu initiieren und zu leiten; 2) die Ermittlung des Einflusses dieser Lehrmethoden auf die themenbezogene Wissensstruktur der Schülerinnen und Schüler; und 3) ein Unterrichtsmodell vorzuschlagen das Lehrerkräfte bei der Planung und Umsetzung kognitiv aktivierenden Biologieunterrichtes unterstützt.

Im Rahmen dieser Doktorarbeit wurde dazu eine Vorauswahl von 30 von 47 Biologieunterrichtsstunden (jeweils 45 Minuten) zum Thema "Blut und Kreislaufsystem", die in einer früheren quasi-experimentellen Prä-Postdesign Studie aufgezeichnet worden waren, neu analysiert. Zusätzlich wurde mit einer Biologielehrkraft einer 11. Klasse erarbeitet, wie das vorgeschlagene erklärungsorientierte Unterrichtsmodell dazu beitragen kann, kognitiv aktivierenden Biologieunterricht zu planen und umzusetzen.

Beschreibende Analysen des Biologieunterrichtes zeigten, dass Lehrkräfte meist Aufgaben einsetzen, die auf einer niedrigen kognitiven Ebenen liegen und eine geringe Komplexität der Inhalte aufweisen. Die Analysen zeigen zudem, dass nur wenige Lehrkräfte Fokusfragen verwenden, um den Zweck der Unterrichtsstunde hervorzuheben; darüber hinaus nutzen nur wenige Lehrkräfte erklärungsorientierte, spezifische und herausfordernde Fokusfragen, um sinnvolle Diskussionen einzuleiten.

Mehrebenenanalysen zeigten einen sehr geringen positiven Effekt der schwierigsten kognitiven Aufgaben auf das themenspezifische Wissen der Schülerinnen und Schüler. Es gab jedoch keinen Einfluss höherer Komplexität der Inhalte auf diese Variable.Während die Verwendung von nicht spezifischen oder einfachen Fokusfragen die themenbezogene Wissensstruktur der Schülerinnen und Schüler nicht vorhersagen kann, ist dies bei Verwendung von spezifischen und herausfordernden Fokusfragen durchaus der Fall. Darüber hinaus zeigte die Zusammenarbeit in der Unterrichtsgestaltung mit der Biologielehrkraft einer 11. Klasse, wie das erklärungsorientierte Unterrichtsentwurfsmodell dazu beitragen kann, kognitiv aktivierende Unterrichtsstunden zu planen und umzusetzen.

Während die deskriptiven Ergebnisse dieser Studie insgesamt deutlich machen, dass lehrerzentrierter, faktenbasierter Unterricht den deutschen Biologieunterricht prägt, zeigen die korrelierenden Ergebnisse einen geringen positiven Einfluss von kognitiv aktivierenden Instruktionsansätzen auf die Wissensstruktur der Schülerinnen und Schüler. Zusätzlich gaben das erklärungsorientierte Unterrichtsmodell und die exemplarische Biologieunterrichtsstunde der 11. Klasse einen Einblick darin, kognitiv aktivierenden Biologieunterricht zu planen.

Insgesamt befürworten die Ergebnisse dieser Doktorarbeit die Verwendung des kognitiv aktivierende Lehrmodells im regulären Unterricht, um den Biologieunterricht zu reformieren.

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1. Introduction

International science and mathematics assessment studies like PISA (Programme for International Student Achievement) and TIMSS (Trends in International Mathematics and Science Study) have highlighted that students from countries like Finland, Japan, South Korea, and China performed consistently better than their counterparts in Germany (Geller, Neumann, Boone, & Fischer, 2014; Organisation for Economic Co-operation and Development (OECD), 2001, 2004, 2007, 2010; Park, 2013). Moreover, the ROSE (Relevance of Science Education) survey highlighted concerns with regard to students attitudes and interest in classroom science and also STEM (Science, Technology, and Mathematics) related careers. The ensuing discussions led the policy makers to review and reform the national science education policies in their respective countries. The recent policy reforms have stressed that, in the current age of information and technology, future scientific jobs would require the workforce to respond to non-routine tasks and problems. Science education should thus move away from imparting domain-related knowledge to facilitating students in acquiring the competencies that are essential to succeed in these professions (Baartman, Bastiaens, Kirschner, & van der Vleuten, 2007; Kultusministerkonferenz (KMK), 2005; National Research Council (NRC), 2012).

Teaching effectiveness researchers have responded to these policy recommendations by investigating instructional approaches that can help cultivate students' STEM-related competencies. Cognitively activating instructional approach is one such approach that has been used to compare and describe high quality education (Förtsch et al., 2016; Klieme and Bos, 2000; Kunter et al., 2007; Lipowsky et al., 2009; Nawani et al., 2016). This instructional approach included three key dimensions: teaching complex and interconnected content, use of challenging tasks, and use of thoughtful discourse. This doctoral research endeavored to contribute to the current discussions on instructional quality by analyzing two of these three individual dimensions of cognitively activating instruction: teachers' use of challenging tasks and teachers' use of thoughful disocurse practices. Additionally, the last segment of the dissertation demonstrates how epistemic activities underlying scientific explanation construction can be used to plan cognitively activating biology lessons.

1.1. Models of Classroom and School Learning

Over the past several decades, researchers have proposed a variety of classroom and school learning models that not only depict the instructional quality features but also the school, context, and individual level factors that affect students' outcomes. The first such model was developed by Caroll (1963), who defined school learning as a function of the *time spent* divided by the *time needed*. He further defined the variable 'time spent' as a product of time allocated for learning and the time a student is willing to spend on a given task, and 'time needed' as a product of students' aptitude, prior knowledge and instructional quality. To summarize briefly, Carroll's model stressed that time is the most important factor that predicts learning, while the variables related to individual students' characteristics or instructional quality moderate this relation by indirectly influencing the time needed for learning or accomplishing any given task. In contrast, Bloom (1968) suggested that instructional quality is a key determinant of students' achievement gap. He further described five key aspects of planning high-quality instruction: organization of content into smaller units, formulating specific learning objectives for instruction, devising formative and summative assessment for instructional units, planning instruction to include ample learning opportunities, and allocating sufficient time to learn the content. He insisted that that use of mastery learning techniques could ensure that all students achieve the same level of learning in any given discipline. The later models extended or refined these classroom learning models by including new levels such as school, culture, and context or by refining one or few specific levels such as instructional quality or culture.

Walberg's (1981) and Proctor's (1984) extended Caroll's time learning model by adding school, teacher, and student level factors that influence student achievement; likewise, Huitt (1995) added context level factors that predict student outcomes. He further categorized the variables related to school, classroom, teacher characteristics, individual characteristics, and the cultural context to present a holistic model of school learning. Proctor (1984) further advocated a cyclical relationship between these levels; for instance, modifying variables at the school levels could enhance students' learning, which in effect will enhance their motivation and interest towards learning the subject matter. This, in turn, could affect teachers' beliefs, attitudes, and their instructional approach when teaching the subject matter.

1.2. Approaches to Research on Teaching

Classroom and school learning models described above have extensively guided the quantitative and qualitative research on teaching effectiveness. For example, Caroll's model guided the research-on-time studies that investigated how variables such as nature of tasks, time allocated for tasks, and student engagement in tasks predicted school learning. Similarly, the comprehensive classroom and school level learning models guided the process-product research on teaching effectiveness. In respect of research on teaching effectiveness, the term 'process' implies teacher behavior that caused the change in student behavior or learning while the term 'product' refers to students' cognitive or affective outcomes. The process-product studies typically define and quantify one or few specific teaching conditions and determine their causal relations with students' cognitive and affective outcomes. However, Doyle (1977) and Dunkin & Biddle (1974) contested that student characteristics such as their interest or motivation as well as the teacher characteristics like attitude and subject matter knowledge influence the teaching conditions, which in turn influence the student achievement. Researchers in the recent times have thus refined their study designs to include presage variables (i.e. teacher behavior or teacher characteristics), the context variables or moderators (i.e. student characteristics or environmental conditions), the process variables (i.e. teaching conditions, classroom activities, learning opportunities for students) and the product variables (i.e. student cognitive and affective outcomes). Such refined study designs have enabled the teaching effectiveness researchers to manipulate and analyze a variety of predictor, moderator, and mediator variables that together determine high-quality instruction.

1.3. Domain-specific Aspects of Instructional Quality

Quantitative approaches to research on teaching have successfully used the process-product design approach to identify teaching behaviors that together define high- quality instruction (Neumann, Kauertz, & Fischer, 2012). Teaching effectiveness meta-analyses and review works such as Anderson (1983), Brophy and Good (1986), Fraser (1987), Hattie (2009), and Seidel and Shavelson (2007) have comprehensively summarized the instructional characteristics that predict student achievement. However, most of these works have analyzed the general features of instruction like classroom management, direct versus problem-based instruction, teacher feedback, or teacher-student relationship, in order to describe the characteristics of high-quality instruction. Here, the term *general criteria* implies a set of instructional characteristics that are not related to the subject matter being taught. In contrast, *the domain specific criteria*, which include both *content specific* and *subject specific criteria*, are closely linked to subject matter and knowledge generation practices used in a domain. Domain-specific researchers have long contended that the heavily researched general criteria of teaching effectiveness cannot fully explain the differences in students' affective and cognitive learning outcomes in specific domain areas such as mathematics, physics, chemistry, and biology. Therefore, the domain-specific criteria should be carefully considered when defining the key features of high-quality instruction (Seidel & Shavelson, 2007). For example, within the context of biology education, teaching interconnected biology content is an important content specific criterion; at the same time, formulating scientifically oriented questions, experiments, real-life objects and models are closely associated with the core practice used in the biology domain (Schörnborn & Bögeholz, 2012; Wadouh et al., 2014; Wüsten, 2008; Wüsten, Schmelzing, Sandmann, & Neuhaus, 2011). Recent studies have thus focused on investigating the domain-specific teaching features, with an aim to present an all-encompassing-view of instructional quality.

1.4. Cognitively Activating Instruction

Cognitive activation is a mental state in which an individual is either consciously and recurrently thinking about a concept or an idea, or this idea is readily retrievable when processing new information or a problem scenario (Lipowsky, 2009; Wagner & Smart, 1997). Cognitive activation can thus be considered an important quality of high-quality instruction: It ensures sustained and thoughtful engagement with the scientific concepts, ideas, and practices.

Cognitive activation is one of the widely investigated domain-specific features of high-quality instruction. Cognitive activation is both content-specific and subject-specific, as it depends on the conceptual ideas being discussed, the learning stage, and the learner's perception of cognitive demands in any given instructional situation (Klieme, Pauli, & Reusser, 2009; Lipowsky et al., 2009; Pauli, Drollinger-Vetter, Hugener, & Lipowsky, 2008). As cognitive activation cannot be directly observed, empirical researchers have offered a wide variety of definitions and measurement strategies to analyze this construct. We discuss some of these definitions below.

The German extension of PISA 2003 study defined cognitive activation as teachers' use of cognitively demanding tasks that not only activate students' prior knowledge but also challenge their beliefs. Further, it also occurs when students are required to justify or explain their answers (Kunter et al., 2006). Baumert et al (2004) utilized students' and teachers' self-reports on questionnaires to examine cognitive activation in lessons. The questionnaire included scales such as cognitively demanding tasks, insisting on explanation and justification after students' answers, and handling cognitively outstanding student utterances (Baumert et al., 2004; Kunter et al., 2005). However, this study found that students and teachers reports varied considerably while evaluating the same lesson or instructional unit.

Another method to investigate cognitive activation relied on analyzing tasks and teaching material used in individual lessons. Within the COACTIV project, the 'teacher designed tasks' and 'worksheets' were analyzed to measure cognitive activation in the lessons (Kunter et al., 2007; Jordan et al., 2008). According to this study, cognitive activation comprises all learning opportunities that facilitate deeper engagement with the subject matter; it involves instructional situations that spur students to make cognitive connections between new information and previously learned information. Teacher designed tasks were first categorized into calculative, conceptual, and practical tasks. In the next step, these tasks were analyzed for their level of difficulty or cognitive demand. These studies found that German teachers usually set up low cognitive demand tasks to develop the topic-related content. These findings were in line with the results reported in the earlier studies, which found that German teachers mainly used a question-development approach and non-challenging, short answer questions to teach content (Hiebert et al., 2003; Jatzwauk, 2007). The quality of instruction in physics lessons (QUIP) study also analyzed tasks assigned in a lesson to measure cognitive activation. However, this study defined cognitive activation as a fit between the difficulty or the cognitive processing level of teacher tasks and students' answers for examining the cognitive activation in physics lessons (Ergönec, Neumann, & Fischer, 2014).

More recent studies have used a video-based direct observation technique to measure the cognitive activation potential of individual lessons or teaching units (Förtsch et al., 2017; Hugener, Pauli, & Reusser, 2007; Lipowsky et al., 2008). These studies have utilized the multidimensional rating manuals to measure the cognitive activation potential of entire lessons (e.g., Förtsch et al., 2017; Hugener et al., 2007; Lipowsky et al., 2008). In these studies, cognitive activation has been described as a set of instructional strategies promoting deeper engagement with the content to develop a conceptual knowledge base. Cognitively activating instruction integrates three key dimensions: the teaching of complex and interconnected content, the use of challenging tasks to orchestrate classroom interactions, and the use of thoughtful-constructive discourse practices to activate and challenge students' prior conceptions (Klieme et al., 2006; Lipowsky et al., 2008). These studies not only reported that cognitive activation was higher in problem-solving and discovery teaching patterns, but also demonstrated positive relationships between the cognitive activation potential of the lessons and students' cognitive as well as affective outcomes. However, it is yet unknown, how the individual dimensions of cognitively activating instructional practice influenced students' outcomes (Nawani et al., 2017).

Taking into consideration the theoretical definitions of cognitively activating instruction and the measurement approaches used so far, we offer three theoretical perspectives as lenses to examine the individual aspects of cognitive activation in biology lessons: 1) the complex and interconnected content lens, 2) the challenging tasks lens, and 3) the thoughtful-constructive discourse lens. Each of these lenses translates into unique teaching features, which could be objectively examined in order to determine their influence on students' outcomes (see Figure 1).

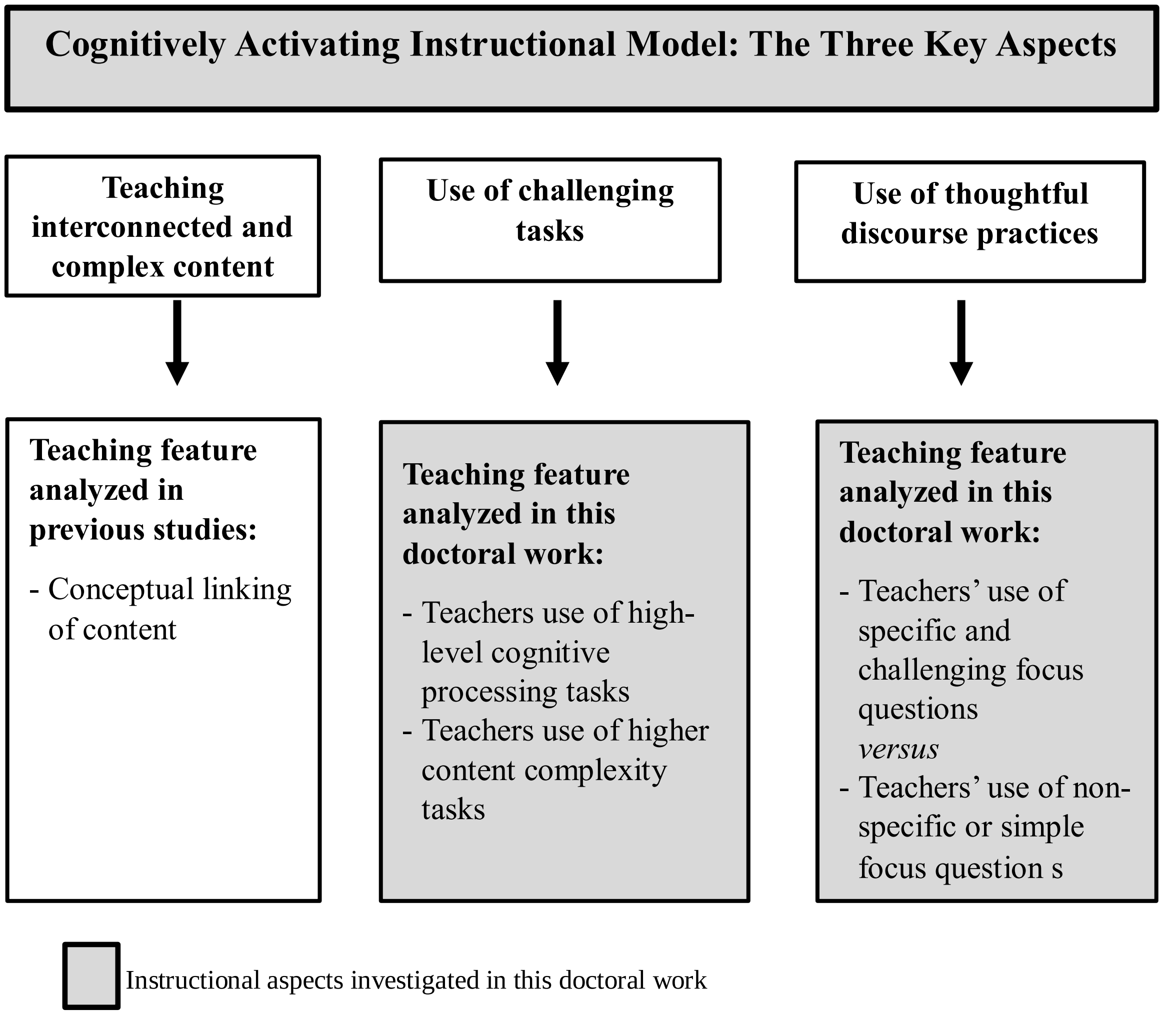

Figure 1.

Translating the three aspects of cognitively activating instructional approach into observable teaching features

1.4.1. *The Complex and Interconnected Content Lens*

The theoretical literature on structure and organization of biology content has described the following four levels of biology knowledge: knowledge of facts or terms; knowledge of concepts; knowledge of scientific principles; and knowledge of underlying fundamentals or disciplinary core ideas. The literature also emphasizes that these knowledge types are deeply interconnected and that domain experts in the field have acquired the conceptual understanding of these interconnections (Ausubel, 1968; KMK, 2005; Schörnborn & Bögeholz, 2008). Recent reforms in science education have, thus, emphasized that biology classrooms should engage learners in constructing horizontal and vertical interconnections between and among these knowledge types. Schörnborn and colleagues (2008, 2010) emphasized that conceptual linking of subject matter stimulates higher-order cognitive processing of the information provided. In other words, it cognitively activates learners to ponder about the subject matter and thus, refine and extend their topic-related knowledge structures.

Earlier studies on teaching effectiveness have attempted to analyze 'conceptual linking' or in other words, 'complexity of the content taught' in mathematics and science lessons using the video-based lesson observation approach. The TIMS (Trends in International Mathematics and Science) studies -1995, 1999 studies first attempted to describe and compare the content complexity observed in the lessons collected from countries like Australia, Germany, Japan, and the Netherlands. These studies found that teacher utterances and tasks in higher achieving Japanese and Australian classrooms focused on conceptual linking of different types of knowledge (Hiebert et al., 2003; Roth et al., 2006; Stigler & Hiebert, 1997; Stigler et al., 1999). They also found that mathematics and science teaching in countries like Germany and the United States focused on transmitting factual or procedural level knowledge about the topics being taught (Hiebert et al., 2003; Klieme & Bos, 2000; Stigler et al., 1999). However, these studies did not correlate teaching features with student achievement. The more recent studies have thus focused on analyzing the interconnectedness of the topic-related content taught in the physics, chemistry, and biology lessons as well as ascertaining their relationship with students' topic-related knowledge. Neumann et al. (2008, 2010) and Wadouh et al. (2014) developed elaborate coding protocols to analyze the linking level of teacher utterances (i.e. both teacher statements and teacher initiated tasks). These studies found that students in higher-linking physics and biology classes acquire more knowledge as compared to the lower-linking classes. However, the chemistry segment of these studies could not find any relation between knowledge linking and students' outcomes. To conclude, conceptual linking, an important aspect of cognitively activating instruction, has already been widely investigated in the literature; the results of the empirical studies revealed that teaching interconnected and complex domain-related content predicts student learning in biology and physics classrooms. Thus, in this doctoral research, we focused on analyzing the other two aspects of cognitively activating instruction: teachers' use of challenging tasks to orchestrate content-related interactions, teachers' use of focus questions to initiate and direct a thoughtful, meaning-making discourse.

1.4.2. Challenging Tasks Lens

Tasks are the basic instructional element that orchestrate content-related interactions in classroom social settings. Jatzwauk (2007) described tasks as content-related requests to think or act, which usually contain one independent 'task operator'. Task operators are words that are indicative of the instruction to act or think (e.g. name, observe). Tasks facilitate the teaching-learning process by directing students' attention on particular aspects of the content, and by providing cues about what cognitive processes would be required to generate a logical and scientifically acceptable response (Blumenfeld et al., 1991; Doyle, 1983; Doyle, 1988). Tasks, thus, not only determine the specific content that students will learn, but also the thinking processes required to make sense of the subject matter (Stein and Lane, 1996; Stein, Grover, & Henningsen, 1996). Given these definition of tasks, studies should endeavor to analyze the following two characteristics to determine their cognitive activation potential: 1) level of cognitive processing demanded and 2) level of content complexity demanded (Doyle, 1988; Blumenfeld & Meece, 1998; Nawani et al., 2017).

Furthermore, based on the cognitive activation construct described in the previous section, challenging or cognitively activating tasks could be defined as teacher initiated questions, activities, or problems that would facilitate 1) high-level cognitive processing of information to construct new representations based on the information provided, 2) deep level engagement with the content to explain or construct new conceptual links. Here, the term high-level cognitive processing refers to cognitive thinking behaviors, required to construct new relationships or representations based on the information provided. To elaborate this further, high-level cognitive processing tasks can be defined as information processing requests that require learners to go beyond mechanical recall and construct new relations or representations by interpreting, analyzing, or evaluating the information provided. In contrast, low-level cognitive processing tasks can be defined as the information processing situations that require learners to recall, paraphrase, reorganize, or summarize the pre-existing topic-related information (Bloom, 1956; Krathwohl, 2002; Resnick, 1987; Newman, 1990). Similarly, the higher content complexity tasks refer to the information processing requests that require students to explain the conceptual links (Hiebert et al., 2003). To put it another way, higher content complexity tasks require students to explain: 1) the relations between facts (i.e. conceptual connections) or 2) the relations between concepts and principles (i.e. generic concepts or generalizations) (Förstch et al., 2017; Nawani et al., 2016; Schörnborn & Bögeholz, 2008). Contrarily, the lower content complexity tasks refer to teacher-initiated tasks or activities that require learners to recall or paraphrase terms, single facts, or definitions related to the topic being taught (Fischer, Glemnitz, Kauertz, & Sumfleth, 2007; Neumann, Fischer; & Sumfleth, 2008, Wadouh et al., 2014).

To summarize, the challenging tasks could be a proximal source of cognitive activation. It is thus essential to analyze this dimension, in order to determine the teaching effectiveness of cognitively activating instruction.

1.4.3. Thoughtful-constructive Discourse Lens

Another important aspect of cognitively activating instruction is the thoughtful development of conceptual level content. With an aim to engage learners in building powerful topic-related ideas, thoughtful discourse entails careful structuring of sense making discussions around scientifically oriented questions (Brophy, 2000). A thoughtful discourse begins by activating students' pre-instructional conceptions or ideas, which are then negotiated, to build content-related understandings (Driver & Easley, 1978; Strike and Posner, 1992). To put it another way, the tension between students' prior knowledge and the scientifically accepted information facilitates knowledge construction. Such meaning making discussions do not rely upon short-answer or factual recall questions; rather learners negotiate their preconceptions and ideas in the classroom social setting (Forbes & Davis, 2010; Lipowsky et al., 2008; Mayer, 2002; Vygotsky, 1978). Teachers often use real-life problems or scientifically oriented questions to initiate and anchor such social negotiations in which learners construct and communicate relationships among and between facts and ideas. Thus, learning often occurs at this zone of proximal development, where students with the help of a teachers' guidance engage in social construction of knowledge. In sum, thoughtful discourse entails activation of learners' prior knowledge and preconceptions, meaning making discussions around scientifically oriented questions, and conceptual linking to build content-related understandings. Forbes and Davis (2010), Krajcik & Mamlok-Naaman (2006), and Nawani et al. (2017) emphasized that teachers' use of 'how' and 'why' type explanation-oriented focus questions can help create dialogic-thoughtful discourses. Such questions highlight one or few specific phenomena or life processes and thus direct the classroom teaching-learning processes on co-constructing scientific explanations. To put it another way, phenomenon or life process-based explanation oriented focus questions encourage conceptual linking of the topic-related information: students use higher-level cognitive processes and engage in sense-making discussions to arrive at a scientifically acceptable explanation of the focus question. Moreover, teachers' use of focus questions at the beginning of a lesson not only highlights the purpose of this lesson but also activates learner's prior conceptions or ideas, rather the factual knowledge about the topic being taught (Schwille, Numedahl, Kruse, & Hvidsten, 2011). Conversely, the authors asserted that teachers' use of 'what-when-which' type description-oriented focus questions promoted surface level engagement with the content. In other words, teachers need short-answer or factual-recall questions to explore scientific terms or isolated facts required to answer these questions. Such monologic interactions require low cognitive level and low content complexity questions to stimulate prior factual knowledge recall and to highlight and review the canonical scientific information presented in the lesson.

In conclusion, focus questions that drive the thoughtful sense-making discussions are an important aspect of cognitively activating instruction. Thus, one way to ascertain the effectiveness of cognitively activating instruction is by analyzing the effect of teachers' use of focus questions on students' knowledge.

1.5. Constructing Scientific Explanations

Domain-specific empirical studies have demonstrated the effectiveness of cognitively activating instruction in enhancing students' cognitive and affective learning outcomes (Förstch et al., 2017; Klieme et al., 2001; Lipowsky et al., 2009; Nawani et al., 2016; Nawani et al., 2017; Wadouh et al., 2014). However, it remains unclear how teachers could design cognitively activating lessons. We thus need new lesson-design models that can support teachers in meaningfully integrating the aspects of cognitively activating instruction features into their everyday lessons. Reforms in science education have paved the path for developing such lesson-design models. Bybee (2009) and Chen and Steenhoek (2013, 2014) have shown how inquiry and argumentation cycles could be used to: 1) anchor the classroom teaching-learning process on answering a testable question; 2) integrate high-level cognitive processes or more specifically, the epistemic activities underlying core science practices in regular lessons; and 3) meaningfully engage learners in constructing new content-related understandings. However, these lesson-design models include relatively long phases of planning and conducting experiments; considering the time and resources available to the disposal of science teachers, sometimes these phases cannot be integrated in the everyday lessons. Most importantly, it is not always practically possible to conceptualize investigations on certain complex biology topics, for example, DNA replication or protein synthesis. In sum, teachers often face difficulties in planning inquiry and argumentation-based lessons while teaching such complex topics. It is thus essential to develop more core science practices oriented models that can be used to teach a variety of the topics included in the curriculum.

The construction of scientific explanations is an important core, included in the national science education standards of countries such as Australia, Canada, Germany, and the United States (Council of Ministers of Education, Canada, 1997, 2013; KMK, 2005; NRC, 2012). Scientists very often engage in explanation construction to construct causal-mechanistic accounts of the natural phenomena or life processes they investigate (Brigandt, 2016; Zimmermann, 2007). Scientific explanation construction entails the following key steps: observing a phenomenon and formulating scientifically oriented questions; interpreting first or second-hand data; making causal inferences based on authentic evidence and the underlying theoretical entities; and articulating explanations (Bratten & Windschitl, 2011; Brigandt, 2016; Forbes & Davis, 2010; Krajcik & Mamlok-Naaman, 2006; Sandoval & Reiser, 2004). In this doctoral work, we endeavored to operationalize the key epistemic activities related to the process of constructing scientific explanations and propose a lesson-design model that can support teachers in designing lessons on a variety of both simple to complex biology topics. Additionally, we collaborated with a grade 11 biology teacher to plan and implement a three-lesson unit based on this explanation-oriented lesson-design model.

2. Research Objectives

In the past few decades, teaching effectiveness studies have focused on describing how science and mathematics are taught in different countries and cultures. For example, the TIMSS (1995, 1999) found that science and mathematics teaching in low-achieving countries such as Germany and the United States focused heavily on transmitting factual and procedural level knowledge about the topics under study. Consequently, teachers mostly asked low cognitive level short-answer or factual recall questions to highlight and review this canonical knowledge. On the other hand, higher-achieving Japanese lessons focused on teaching conceptual level knowledge using a problem-based approach to mathematics teaching and a coherent storyline based science teaching approach. Analysis of Japanese lesson videos also revealed that teachers presented high-level cognitive processing situations such as real-life problems, scientifically oriented questions, authentic data interpretation activities, and investigating phenomena using real-life objects and models to promote conceptual linking of topic-related content (Hiebert et al., 2003; Roth et al., 2006). To summarize briefly, German lessons used low cognitive demand tasks or questions to present the knowledge of isolated facts, while Japanese teachers used high cognitive demand tasks or questions to impart content-related understandings. Cognitive activation was thus an important characteristic of high-quality Japanese lessons (Klieme and Bos, 2000).

Empirical studies in science and mathematics education have operationlized this construct to describe the key features of science and mathematics lessons. These studies have successfully demonstrated that cognitive activation is an important domain-specific feature of high-quality instruction (Baumert et al., 2010; Förtsch et al., 2016; Lipowsky et al., 2009; Pauli, Drollinger-Vetter, Hugener, & Lipowsky, 2008). These studies have described the three key aspects of cognitively activating instruction: teaching complex and interconnected content; use of challenging tasks to orchestrate content-related interactions; and a thoughtful-constructive discourse. However, these studies mostly examined the cognitive activation potential of entire lessons based on the teachers and students reports on questionnaires, analysis of tasks and teaching material, or video-based rating of lesson videos. It is thus still unclear how the individual dimensions or aspects of cognitive activating instruction influenced student learning. Additionally, there are hardly any lesson-design models that support teachers to integrate cognitively activating instructional features into their regular practice.

This doctoral research addresses this research gap by describing two of the three dimensions of cognitively activating instruction, how these dimensions influence student learning, and proposes a lesson-design approach that helps plan and implement cognitively activating lessons. The above-stated aims were accomplished within the purview of the following three research objectives:

1) Describing two key aspects of cognitively activating instruction in German biology classrooms: teachers' use of challenging tasks and teachers' use of focus questions
2) Investigating the correlation between these aspects and student learning.
3) Proposing an explanation oriented lesson-design model that supports teachers in using the core science practice of constructing scientific explanations as a process to create cognitively activating learning environments.

The first two research objectives were addressed within papers I and II, while the third aim was addressed in paper III (see Figure 2).

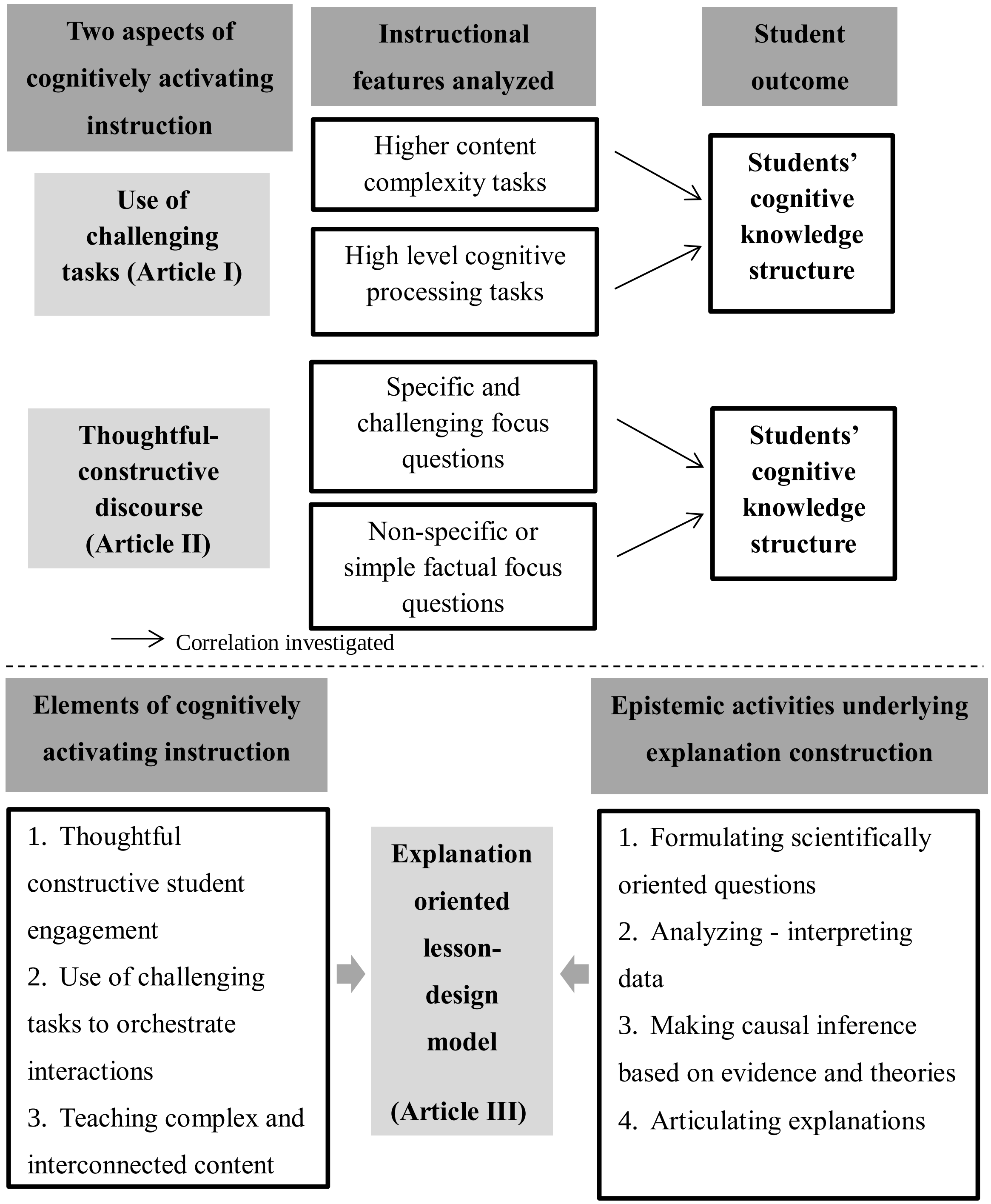

Figure 2.

Overview of research objectives. Analyzing two individual aspects of cognitively activating instruction. Employing epistemic activities underlying explanation construction to integrate aspects of cognitively activating instruction into a lesson-design model.

3. Results

3.1. Publication I

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Influence of Using Challenging Tasks in Biology Classrooms on Students' Cognitive Knowledge Structure: An Empirical Video-study

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Abstract

Empirical analysis of secondary biology classrooms revealed that on average 68% of teaching time in Germany revolved around processing tasks. Quality of instruction can thus be assessed by analyzing the quality of tasks used in classroom discourse. This quasi-experimental study analyzed how teachers used tasks in 38 videotaped biology lessons pertaining to the topic 'blood and circulatory system'. Two fundamental characteristics used to analyze tasks include: 1) required cognitive level of processing (e.g., hypothesis building, interpretation or evidence evaluation tasks that require deeper information processing) and 2) complexity of task content (e.g., tasks involving factual, linking or conceptual level content). Additionally, *students' cognitive knowledge structure* about the topic 'blood and circulatory system' was measured using student drawn concept maps (N = 970 students). Finally, linear multilevel models were created with *high level cognitive processing tasks* and *higher content complexity tasks* as class level predictors and *students' prior knowledge*, *students' interest in biology*, and *students' interest in biology activities* as control covariates. Results showed a positive influence of *high level cognitive processing tasks* ($\beta = 0.07$; $p < 0.01$) on *students' cognitive knowledge structure*. However, there was no observed effect of *higher content complexity tasks* on *students' cognitive knowledge structure*. Presented findings encourage the use of *high level cognitive processing tasks* in biology instruction.

Keywords: Challenging tasks, Video-studies, Biology teaching, Concept maps

Influence of Using Challenging Tasks in Biology Classrooms on Students' Cognitive Knowledge Structure: An Empirical Video-study

International studies like the 'Programme for International Students Assessment – PISA' and 'The Third International Mathematics and Science Study – TIMSS' found country-specific differences in the way students performed in science and mathematics tests. Thus, the TIMSS (1995, 1999) video studies were conceptualized to explore unique features of teaching science and mathematics in various countries (e.g., Japan, United States, etc.). However, TIMSS did not investigate the influence of teaching features on students' learning outcomes. Furthermore, Germany participated in the mathematics part of this cross-country study (TIMSS – 1995) and thus German science – especially biology classrooms are rarely investigated (Wadouh, Liu, Sandmann, & Neuhaus, 2014). In that regard, the presented study investigated the way teachers' use of *challenging tasks* (e.g., *high level cognitive processing tasks* requiring deeper information processing; *higher content complexity tasks* involving linking or conceptual level content) in German secondary biology classrooms influenced students' learning outcomes.

The TIMSS - 1999 science video study identified *cognitive activation* as one important characteristic of effective science teaching. *Cognitively activating instruction* can be defined as a teaching practice that encourages deeper processing of new content presented during the classroom discourse (Lipowsky et al., 2009). In science and mathematics classrooms, cognitive activation is usually studied at three different instructional levels: 1) teaching of complex domain content, 2) use of challenging tasks, and 3) practicing thoughtful discourse (See Figure 1). However, teaching effectiveness studies differ in the way they define and operationalize (Kunter et al., 2013). Moreover, these studies usually measure the cognitive activation potential of complete lessons (Förtsch et al., 2015a; Lipowsky, 2009). One recent empirical study found a positive influence of cognitively activating instruction on students' situational interest in biology classrooms. This study rated videotaped biology lessons to determine the cognitive activation potential of complete lessons (Förtsch et al., 2015a). Thus, it is yet unclear whether enhancement in student performance was due to 1) teaching of complex domain content, (2) use of challenging tasks, or 3) practicing thoughtful discourse (see Figure 1). Another study in this regard analysed the 'use of tasks in German biology classrooms' (Jatzwauk, 2007; Jatzwauk, Rumann , & Sandmann, 2008). Jatzwauk et al. (2008) found that *two-third of class time* in a German biology classroom was utilized for processing tasks. Thus, quality of classroom instruction could be assessed by analysing the frequency with which teachers used challenging tasks (e.g., *high level cognitive processing tasks* and *higher content complexity tasks*) during classroom discourse (Blömeke et al., 2006; Klieme & Bos, 2000; Lipowsky et al., 2009). Furthermore, teaching effectiveness studies so far have investigated the influence of teaching features on student outcomes like ‘performance in knowledge tests’ or ‘situational interest’. Thus, *students’ cognitive knowledge structure* (i.e. interconnectedness of students’ knowledge about a topic or domain), an important competence reflecting domain expertise is rarely investigated (Ruiz-Primo & Shavelson, 2005; Yin et al., 2005). To that end, this empirical investigation examined the influence of using challenging tasks on students’ cognitive knowledge structure, measured using student drawn concept maps. To begin with, we first present the literature review guiding this study.

Cognitively Activating Instruction

Pauli, Drollinger-Vetter and Hugener (2008) defined cognitive activation as active, constructive and discursive engagement with domain related content. Cognitively activating instruction can thus be described as ‘use of learning activities or tasks that engage students in developing conceptual level content’ (Kunter et al., 2013). Described below are three features that together depict the cognitive activation potential of science or mathematics lessons (Förtsch et al., 2015a; Lipowsky, 2009).

1) Teaching of complex domain content that includes interconnected facts, biology concepts, principles and disciplinary core ideas (Nachreiner, Spangler & Neuhaus, 2015; Hiebert et al., 2003; Jacobs et al., 2003, 2006; Neumann, Fischer & Summefleth, 2008; Schönborn & Bögeholz, 2009; Wadouh et al., 2014),

2) Use of challenging tasks that involve higher order cognitive processing and high content complexity (Blooms, 1972; Craik & Lockhart, 1972; Ergönenc et al., 2014; Hiebert et al., 2003; Jacobs et al., 2003), and

3) Practicing thoughtful discourse that constructively engages students in new knowledge generation process (Chi, 2009; Hugener et al., 2009; Mayer 2004, 2009) (See Figure 1).

In order to meaningfully inform the instructional practice, it is important to understand how above mentioned instructional levels influence students' domain knowledge. In that regard, Neumann et al. (2008) and Wadouh et al. (2014) showed a positive influence of teaching complex domain content on *students' cognitive knowledge structure* in physics and biology respectively.

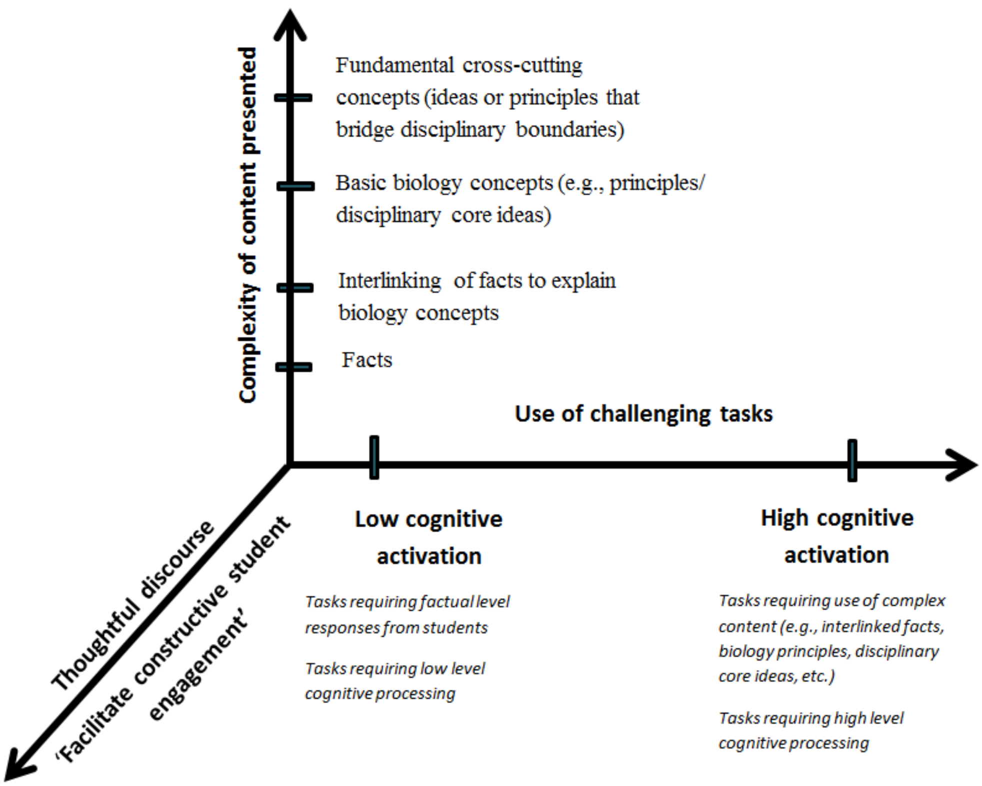

Figure 1: Cognitively activating instruction. Based on the theoretical descriptions presented by Förtsch et al (2016); Lipowsky et al. (2009); Schönborn and Bögeholz (2009); Wadouh et al. (2014).

However, teaching effectiveness studies have advocated the 'use of tasks' (i.e. teacher initiated questions or activities) as an important instructional feature for developing deeper conceptual knowledge in science and mathematics classrooms (Ergönenc et al., 2014; Förtsch et al., 2015a; Jacobs et al., 2003, 2006; Jatzwauk et al., 2008; Lipowsky et al., 2009). Hence, this study analysed the effectiveness of using *challenging tasks* in biology classrooms on *students' cognitive knowledge structure.*

Challenging Tasks

Tasks are basic treatment units that could be used to orchestrate transfer of new domain knowledge (Blumenfeld & Meece, 1988; Bruder, 2003; Doyle 1979, 1983). 'Tasks as classrooms learning opportunities' form an interactive interface between students' already acquired knowledge and new content being taught in lessons (Knoll, 1998). Teachers use tasks to redirect students' attention on specific aspects of content. In that regard, tasks could encourage students to cognitively process the new information and share it with the class for further discussion. To summarize, two elements that can help differentiate tasks used during classroom discourse are: 'required cognitive level of processing' and 'complexity of task content' (Blumenfeld & Meece, 1988). The presented study used these fundamental task characteristics: 'required cognitive level of processing' and 'complexity of task content' to identify *challenging tasks* in 38 videotaped biology lessons.

Two types of *challenging tasks* analysed in this study include:

1) *High level cognitive processing tasks*: Several empirical studies have shown that tasks that require deeper analysis of content enhance students' conceptual understanding and overall performance (Brown, 1994; Klieme & Bos, 2000; Lipowsky et al., 2009; Stein & Lane, 1996). Such tasks include deeper information processing situations such as designing an experiment, formulating a hypothesis, presenting reasons or explanation for a given problem, interpreting or analysing data, reflecting or evaluating a given scenario (Anderson & Krathwohl, 2001; Fischer et al., 2014; Krathwohl, 2002). On the other hand, tasks requiring repetition, enlisting,

classifying or comparing do not engage students in deeper processing of the new information presented during lessons. Hence, this study endeavored to examine teacher initiated tasks for their level of cognitive processing (e.g., High level: analysis, reasoning, interpretation, etc. Low level: repetition, classifying, comparing, etc.) (Anderson & Krathwohl, 2001; Blooms, 1972; Blooms Taxonomy, n.d.; Craik & Lockhart, 1972; Ergönenc et al., 2014; Fischer et al., 2014; Krathwohl, 2002) (See Table 1).

2) *Higher content complexity tasks:* Teaching effectiveness studies have found that mathematics and science lessons usually focus on presenting and reinforcing facts related to the topics being taught (Jacobs, 2006; Neumann et al., 2008; Wadouh et al., 2014). These studies have advocated that mathematics and science lessons must include content as well as tasks that enable students to see how facts can be interconnected to describe: concepts (e.g., facts like 'cytoplasm of red blood cells is rich in hemoglobin' or 'red blood cells help carry gases' can be interlinked to explore how oxygen is transported from lungs to body cells), principles (e.g., antigen-antibody interactions using key-lock principles, gas exchange across thin-walled air sacs

Table 1

Challenging tasks in biology classrooms

Elements that help differentiate tasks: 'Complexity of task content' and 'Level of cognitive processing demanded' (Blumenfeld & Meece, 1988)		
Complexity of task content	Fact level content (Lower content complexity tasks)	Linking or conceptual level content ***(Higher content complexity tasks)***
Cognitive processing level of tasks	Low level cognitive processing situations: Repetition, Summary, Define, List, Classify, Arrange, Compare, Contrast (Low level cognitive processing tasks)	High level cognitive processing situations: Explaining – giving reasons, Designing experiment, Formulating hypothesis, Interpret or analyze data, Reflect –rethink, Evaluate ***(High level cognitive processing tasks)***

or alveoli in lungs can be explained using the principle of diffusion gradient and core domain ideas (e.g., red blood cells have flexible, disc-like shape to increase the surface area for gas exchange and to enhance the flexibility to fit through narrow blood vessels is an example for the core domain idea 'form follows function') (Hiebert et al., 2003; Jacobs et al., 2003, 2006; Neumann et al., 2008; Wadouh et al., 2014).

In that regard, quality of instruction can be described by investigating the content complexity of tasks used during the lessons. Analysis of TIMSS teaching videos showed an extensive use of higher content complexity tasks (40%) in higher achieving Japanese mathematics classrooms (Hiebert et al., 2003). Similarly, analysis of TIMSS science videos revealed that most activities and teacher utterances in higher achieving Japanese and Australian science classrooms focused on conceptual linking of domain content (Jacobs et al., 2006). In that regard, the presented study investigated the content complexity of tasks used by German biology teachers. Teacher initiated tasks were analysed for use of factual (e.g., Name the components of blood) and linking or conceptual level content (e.g., Why can't we transfuse blood from a donor with a different blood group?) (Nachreiner et al., 2015; Neumann et al., 2008; Schönborn & Bögeholz, 2009; Wadouh et al., 2014) (See Table 1).

Students' Cognitive Knowledge Structure in Biology

Learning involves assimilating new knowledge and connecting it with prior knowledge to form an integrated knowledge structure about any topic (Ausubel 1963, 1968). Ausubel (1963) described two ways of acquiring knowledge: rote and meaningful learning. Rote learning focuses on assimilating knowledge of isolated facts, whereas meaningful learning involves assimilation of new information and linking it with prior knowledge to develop a more complex knowledge structure. Research in this regard has shown that experts possess complex cognitive knowledge structures, while novices have simpler knowledge structures, which consist of isolated facts or propositions (Duschl, Schweingruber & Shouse, 2007; Glaser, 1991). Several empirical studies found that students who acquired interconnected and integrated knowledge could remember content more successfully than students who acquired knowledge in the form of isolated facts (Osborne & Wittrock, 1985). Thus, meaningful learning involves continuous refining of knowledge structures (about any given topic) to develop expertise in the domain (Mayer, 1998; Resnick, 1989).

Knowledge structure in domains like biology consists of interconnections or links between biology concepts and appreciation of underlying principles or disciplinary core ideas (Nachreiner et al., 2015; Wadouh et al., 2014). However, school assessments rarely focus on evaluating *students*' *cognitive knowledge structure* about the topics being taught in classrooms (Ruiz-Primo & Shavelson, 2005; Yin et al., 2005). To that end, our study examined the relation between teacher initiated tasks used during biology classroom discourse and *students*'*cognitive knowledge structure,* evaluated using the concept mapping exercise.

Concept Maps

Concept mapping is a valuable tool in assessing *students' cognitive knowledge structure* about a certain topic (Ausubel, Novak, & Gowin, 1970; Zele & Lenaerts, 2004). Concept maps reflect conceptual terms and interconnectedness of terms related to a topic. Concept mapping exercises involve both linear and hierarchical structures of knowledge (Kinchin, 2011). Several scoring systems have been suggested for assessing the linear and hierarchical structures (or connections) in concept maps (Ruiz-Primo & Shavelson, 2005; Zele & Lenaerts, 2004; Yin et al., 2005). The quantitative scoring systems count the number of valid structures or propositions (Ruiz-

Primo & Shavelson, 2005). A valid proposition is a structure that includes two conceptual terms connected by a labeled arrow. The qualitative scoring systems rely upon expert evaluation to analyse the content and quality of maps (Kinchin, 2011). Quantitative methods are hence objective and more reliable (Zele & Lenaerts, 2004). Wadouh et al. (2014) used the quantitative scoring method to evaluate concept maps for variables like: 1) Number of relations (propositions) drawn, 2) Number of cross-relations drawn, 3) Number of separate networks or concept maps drawn 4) Number of correct relations drawn and 5) Number of relations with deeper explanations for connections drawn. Here, the term cross-relation can be defined as a relation between the concept (or term) of the topic 'blood and circulatory system' and concepts (or terms) of other topics like immune system, respiration, etc. We used above mentioned variables related to concept maps, while investigating the influence of teachers' *use of challenging tasks* on *students' cognitive knowledge structure.*

Table 2

Principal component matrix (Varimax-rotated) of 4 variables analyzed in student concept maps

Student concept map variables	**Loading**
Number of correct relations drawn	.91
Number of total relations drawn	.89
Number of relations with deeper explanation for connections drawn	.68
Number of concept maps drawn	.65

The matrix shows the loadings of the 4 variables on one factor. Only loadings > .4 are shown.

Students' Prior Knowledge

According to constructivists', learning is an active process of acquiring new knowledge in a way that it is linked with pre-existing knowledge (Gerstenmaier & Mandl, 1995). Acquisition of new knowledge thus leads to extension or correction of learners existing knowledge structures

(Wadouh, 2008). Several studies have found that availability of relevant knowledge is a crucial parameter for acquiring new knowledge (Alexander et al., 1994; Garner & Gillingha, 1991). *Students' prior knowledge* is thus an important parameter in determining their success in acquiring new knowledge and developing complex knowledge structures. In that context, we used *students' prior knowledge* (related to the topic) as a control covariate for this research investigation.

Students' Motivation and Interest to Learn Biology

Motivation can be described as individual preferences or reasons that lead to a certain behavior (Gredler, Broussard & Garisson, 2004; Guay et al., 2010). Self-determination theory described different types of achievement motivations based on the reasons that lead to a behavior or action (Deci & Ryan, 1985). Based on this theory, intrinsic motivation could be described as individual engagement in an activty because they feel rewarded by completing the task. In the classroom context, such a behavior reflects autonomy where student involvement is sustained due to their inherent interest in the content, discussion or activities presented by the learning environment (Krapp, 2002; Wadouh et al., 2014). On the other hand, extrinsic motivation could be described as individual engagement in tasks to receive an external positive outcome or avoid a negative outcome. Extrinsic learning motivation could thus be described as student engagement in learning activities to achieve good grades, teacher approval, or just to avoid negative teacher response. Schiefele and Schreyer (1992) found a positive relationship between intrinsic learning motivation and student achievement.

However, researchers argued that achievement motivation does not account for content-specificity of learning motivation and thus it is important to explore how interest with regard to a specific context, theme or activity can influence achievement (Schiefele, Krapp, Prenzel, Heiland, & Kasten, 1983). Individual interest in that regard could be defined as a persons' preference or affinity for certain themes, objects or activities. This person-object interaction is also referred to as 'object engagement' (Krapp, 2002). In classroom contexts, this engagement is deliberately aimed at enhancing the student understanding of various topics. Researchers suggest that such intentional learning environments could gradually enhance student disposition to learn about a given topic or domain. Empirical research in that regard has also found that thematic interest is an important predictor of performance (Prenzel, 1988; Krapp et al., 1992).

Thus, the presented study used motivation (intrinsic and extrinsic) and interest (interest in the subject, interest in subject related activities) as control variables while investigating the hypotheses defined for the study.

Video Based Observation of Classroom Instruction

Video based direct observation is increasingly being used to analyse deeper features of classrooms instruction and correlating them with student learning outcomes (Rakoczy et al., 2007). The TIMSS - 1999 study compared mathematics teaching in seven countries that include Australia, Czech Republic, Hong Kong, Japan, Netherlands, Switzerland, and United States. This study found that more than 50% of tasks in high-achieving Japan emphasized on making connections between mathematical facts, concepts and procedure. Moreover, 40% of tasks in Japanese mathematics classrooms demanded high level procedural complexity (Hiebert et al., 2003). A similar study about German physics classrooms found that 80% of teacher initiated tasks demanded lower order cognitive processing i.e. reproducing factual knowledge (Seidel et al., 2007). One recent study analysed high-complexity and high-cognitive-processing tasks in videotaped grade 6 biology lessons. This study found a positive influence of high-cognitive-processing tasks on students' factual knowledge and structural knowledge (Förtsch, 2015b). Another study analysed tasks in grade 9 secondary biology lessons. This study reaffirmed that German biology lessons were usually orchestrated using low cognitive level tasks (Jatzwauk et al., 2008). This study found a positive influence of *teachers' use of tasks* on students' knowledge, specifically when students showed very little topic related prior knowledge. Thus, the presented study used video based observation method as a tool to analyse teachers' use of *challenging tasks* in German biology lessons.

Hypotheses

To summarize, several empirical studies have investigated the influence of cognitively activating instruction on students' learning outcomes like situational interest and knowledge test. However, the presented study investigated the influence of using *challenging tasks (high level cognitive processing tasks & higher content complexity tasks)* in classrooms on *students' cognitive knowledge structure*, when controlled for students' prior knowledge related to the topic, motivation and interest related variables. Therefore, we investigated following hypotheses in the study presented here:

H1: There is a positive influence of using *high level cognitive processing tasks* on the *students' topic related cognitive knowledge structure*, measured using student drawn concept maps (Brown, 1994; Klieme & Bos, 2000; Lipowsky et al., 2009; Stein & Lane, 1996).

H2: There is a positive influence of using *higher content complexity tasks* on *students' cognitive knowledge structure*, measured using a concept mapping exercise (Jacobs et al., 2003, 2006).

Method

The presented study is part of a larger teaching effectiveness project funded by Federal Ministry of Education & Research (BMBF). We used a quasi-experimental pre-post design to collect classroom teaching videos and student tests - questionnaire data. All data were collected from Gymnasium secondary schools of the state North Rhine-Westphalia, Germany (Wadouh, 2008; Wadouh et al., 2014).

Research Design

In the first phase of data collection, students from 47 participating grade 9 classrooms were given: 1) a pre-test to evaluate prior knowledge about the topic and 2) an interest and motivation

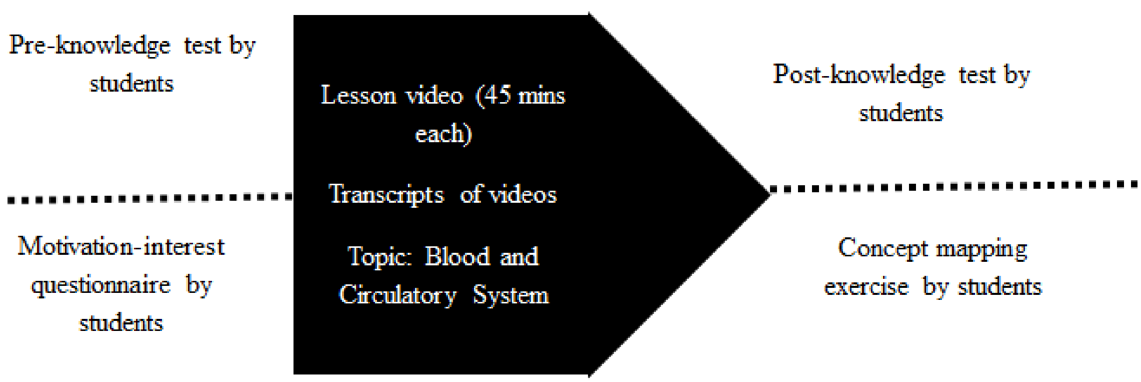

Figure 2. Pre-post design for collecting data used in this empirical investigation.

in biology questionnaire. In the second phase, we videotaped one biology lesson per teacher on the topic 'blood and circulatory system'. In the final phase of data collection, all students completed: 1) a post-unit knowledge test and 2) a concept mapping exercise (See Figure 2). Some of the previous studies that used this dataset to describe biology teaching processes include: Jatzwauk (2007), Wüsten (2010), Wadouh et al. (2014), etc.

As school and teacher participation in the study was voluntary, we collected videos and other data from biology teachers who gave their consent in the beginning of this study. Furthermore, this study examined the correlation between 'instructional components' and students' knowledge structure about a given topic. Hence, we standardized the content by videotaping lessons pertaining to one topic 'blood and circulatory system'. Videotaping lessons pertaining to a common topic helped administer topic related pre-post tests and post unit concept mapping exercises that helped evaluate students' knowledge about 'blood and circulatory system' (Hugener et al., 2009; Praetorius, Pauli, Reusser, Rakoczy & Klieme et al., 2014).

Participants

Forty-seven biology lesson videos (approx. 45 min each) on the topic 'blood and circulatory system' were collected from grade 9 classrooms (N = 1214 students) of the state North Rhine-Westphalia. Teachers who participated in this study were on average 46 years old (min = 28, max = 60, SD = 10; N = 47) with 18 years of teaching experience (min = 1, max = 31, SD = 11; N = 47). However, our study examined 38 out of 47 biology lesson videos. Here, seven out of 47 classrooms were dropped because students from these classrooms could not participate in the concept mapping exercise. Two more classrooms were dropped because these lessons had very few utterances related to the content. Average class size of participating 38 classrooms was approximately 26 students (min = 20; max = 31; SD = 2.4).

Instruments

Concept maps. Students constructed concept maps based on 15 terms related to blood and circulatory system that include: Heart, Blood groups, Cellular Respiration, Circulation, Blood, Muscles, Nutrients, Blood donation, Blood cells, Pathogens, Oxygen, Arteries, Blood Pressure, Exercise, and Energy (Wadouh, 2008). Quantitative scoring system based on a frequency was used to evaluate concept maps (Friege & Lind, 2000; Stoddart, Abrams, Gasper & Canaday, 2000). Student drawn concept maps were scored for the following variables:

1) number of concept maps drawn (i.e. whether the concept maps consisted of disconnected networks);

2) number of total relations with legible labels (i.e. the number of relations and number of cross-relations drawn);

3) number of relations drawn with technically correct explanations;

4) number of relations drawn with deeper explanations for the relations drawn

We would like to mention here that 'number of total relations with legible labels' (i.e. variable 2 mentioned above) included two sub-variables: 1) total number of relations drawn between terms pertaining to the topic 'blood and circulatory system' (e.g., blood and heart; blood and blood pressure) and 2) total number of cross-relations drawn between terms related to the topic 'blood and circulatory system' and other topics like 'immune biology' (e.g., blood and pathogens; blood cells and cellular respiration).

Analysed by two raters, student drawn concept maps showed satisfactory values of Cohens' kappa coefficients (κ) (Landis & Koch, 1977; Wirtz & Caspar, 2002). Kappa values for inter-rater agreement were: number of total relations: $\kappa = 0.93$, number of correct relations: $\kappa = 0.61$ and depth of description used to explain the relation between two terms: $\kappa = 0.73$ (Wadouh, 2008). This data was also used for another study to investigate the influence of *teaching interconnected complex domain content* on *students' cognitive knowledge structure* (Wadouh, 2008; Wadouh et al., 2014).

However, we used *principal component analysis with varimax rotation* to extract factors from the four concept maps variables mentioned above. As depicted in Table 2, the principal component analysis resulted in a single component. No subscales could be extracted. Hence, the z-standardized values of four concept map variables were added together to form one aggregate variable: *students' cognitive knowledge structure.* Four variables that were z-standardized and added to form this variable included: 1) number of concept maps drawn, 2) number of total relations with legible labels, 3) number of relations with technically correct explanations, and 4) number of relations with deeper explanations for the relations drawn.

Category system for video coding. A three-step coding scheme was theoretically devised to analyse teachers' use of *challenging tasks* in lesson videos. All 38 videos were event coded with the software Videograph (Rimmele, 2002). Thus, each teacher initiated task (an event) was coded in three-steps described below:

1) At first, the coders observed the teacher initiated tasks and coded them for 'new teacher initiated tasks' (e.g., why are red blood cells important?) and 'connecting teacher tasks' - used as links, connectors to continue the discussion (e.g., let me ask someone else, you: why are they (i.e. red blood cells) important?) (See Table 3). Cohens' kappa coefficient ($\kappa = 0.72$) indicated a substantial inter-rater agreement between observers coding new and connecting teacher tasks.

Table 3

New and connecting teacher initiated tasks (function of tasks during teacher-student interactions)

Category	Description and indicators	Example
New teacher initiated tasks	Task or question that begins a new sequence of teacher-student interaction Following events indicate a new teacher initiated tasks: 1. Task that presents new content and facilitates the process of new content development. 2. Task refers to new information, text or artifacts/ material presented in classrooms. 3. First task of teaching conversation 4. Teacher formulates new task without expecting any response to a previous task.	L: Explain how cells are supplied with oxygen. S: The oxygen inhaled via lungs reaches cells. L: What happens to oxygen in cells? (Although teacher uses the same word oxygen in new task but asks about the molecular processing of oxygen in cells). L: What is a blood type? | S: A, B, AB and O. L: And how is knowledge of blood type important for blood transfusion?
Connecting tasks to generate further responses	1. Teacher passes the same task to new student. 2. Teacher reformulates a task (further clarification). However, this new task has same content as the previous task.	L: What is a blood type? | S: A, B, AB and O L: Anyone else, What are blood groups?
Connecting teacher tasks after a student answer	1. Teacher formulates a task after student answer for further clarification, justification, error-correction. 2. Teacher asks for clarification of terms used by student while answering previous task. 3. Task relates to whole or part of student answer.	L: What is a blood type? | S: A, B, AB and zero. | L: What is the meaning of A, B, AB and O? (A, B, AB and O should be better defined). Q: What happens when you mix the blood with the blood of Hanna Tom? | S: It clumped. | L: Why? / How?
None of above	Tasks with no content or tasks which could not be connected to the content being discussed during the lesson.	Where is your assignment? Give me? Did you all bring your books/ student card.

Adapted from (Rixius, 2014 – manuscript in preparation)

Table 4

Cognitive processing level of teacher initiated tasks

Low level cognitive processing (Cognitive objectives levels – Knowledge, Comprehension) (Anderson & Krathwohl, 2001; Blooms, 1972; Blooms Taxonomy, n.d.; Krathwohl, 2002)		
Category	**Description**	**Example**
Repetition tasks	Tasks that ask to reproduce content from information available in written form. Tasks that ask student to repeat content from previous teacher or another students' response.	L: Read text from reading material that describes the living habitat of fishes. L: Repeat Martins' answer.
Summary	Tasks that ask students to concisely summarize content in their own words.	L: What were some key learning points in todays' discourse?
Define, List, Specify terms	Tasks asking for definitions, naming of specific technical biological terms, verification of given definition, examples, analogies, etc.	L: Give names of different types of blood cells. L: Give percent rates of occurrence of different types of blood cells.
Describe	Description of how something works looks, etc. Description of actual circumstances, structures, contexts or procedures with or without pictures, graphs or diagrams.	L: Describe the structure of erythrocytes. L: What relation is shown in this diagram?
Classify Arrange	Characteristics, elements, members should be classified into categories.	L: Arrange the images of immune response to individual texts.
Compare Contrast	Tasks asking to state differences or similarities between elements, members, features, contexts.	L: How are platypus and mammals similar and different from each other?

Adapted from (Rixius, 2014 – manuscript in preparation)

Cognitive processing level of teacher initiated tasks

High level cognitive processing (Cognitive objectives levels – Application, Analysis, Synthesis & Evaluation) (Anderson & Krathwohl, 2001; Blooms, 1972; Blooms Taxonomy, n.d.; Krathwohl, 2002; Fischer et al., 2014)		
Category	**Description**	**Example**
Explain, Give reasons, Justify	Tasks that ask for logical explanation, justification of phenomenon using biology concepts or disciplinary core ideas.	L: Explain why is water the most appropriate habitat for fish/ Explain why fish live in water? L: How do you know that Mr. Roth's blood type is A+
Design an experiment/ Formulate hypothesis	Tasks that ask students to design an experiment and formulate hypothesis to prove a scientific phenomenon or observed process	What factors do you think influence the photosynthetic activity of plant? Formulate hypothesis to investigate various factors
Interpret and Analyze	Tasks that ask students to draw substantive conclusions after evaluating multiple evidences, clues	Observe the results from clumping reactions of various blood antigen-antibodies and explain what Mr. Roth's blood type is?
Reflect, rethink	Tasks that ask students to recheck the answer given by another student to confirm or refute its accuracy	Consider again whether the platypus actually descended from birds?
Evaluation	Asking opinion/ judgment/ justification	Should we donate our organs after death? Should blood donation be a common practice for all healthy human beings?

Adapted from (Rixius, 2014 – manuscript in preparation)

Table 5

Content complexity of teacher initiated tasks

Category	Example
Task content - Fact level	
When a task asks for fact or more facts. The task could ask for a definition, features, specific properties, technical term used in domain.	L: Give me a task of erythrocytes! | S: red blood cells carry oxygen. (Task). L: You know the blood groups A, B, AB, and …? | S: O. (Here's an idea is requested.) L: What do you mean by clumping? | S: agglutination. (You will be asked for a word, the result of a state.)
Task content - Linking level	
When a task requires that students to explain the interconnections between facts or present an explanation for the biology process or phenomenon using a set of interconnected facts. Additionally, linking level tasks could demand explanation about how facts influence each other or a third factor, dependence of two factors on each other, conditions required for occurrence of biological phenomenon, causal relations for biological processes, functional explanation of biological terms, etc.	L: When does agglutination of blood happen? S: In case of injury (temporal condition of agglutination) (own example). Q: What happens during blood clumping? S: Red blood cells are combined. (Process, not concept). Q: What happens if I mix the blood group A antibodies with blood type B blood? S: The antibody B blood group A combine with antigens B blood group B. (interaction between antibodies and antigens except clotting reaction can be observed by an imaging observation).
Task content - Concept level	
When tasks require explanation of causal relation using a biology concept or disciplinary core idea. When a task demands to hypothesize underlying biological concept or disciplinary core idea.	L: Describes the process of oxygen transport at organ level and cellular level. S: The oxygen passes from lungs via pulmonary vein and from there to heart into the aorta. Of the aorta from the oxygen is then transported to the various organs in the body. If you look at the cells, the oxygen is bonded via hemoglobin and either stored or passed over. (You will be prompted for the application of the basic concept levels of the organization or system).

Adapted from (Rixius, 2014 – yet to be submitted)

2) In the second step, each ‘new teacher initiated task’ was coded for level of cognitive processing (i.e. Low level: repetition, summary, list, describe, etc.; High level: explain, justify, formulate hypothesis, interpret, etc.) (See Table 4). Cohens’ kappa coefficient for observers coding high and low level cognitive processing tasks was satisfactory ($\kappa = 0.68$).

3) In the third step, ‘new teacher initiated tasks’ were coded for their level of content complexity (i.e. fact, linking or conceptual level content) (See Table 5). Cohens’ kappa for coding complexity of task content was again satisfactory ($\kappa = 0.72$).

Observer coding from this three-step process were used to report total number of 1) high level cognitive processing tasks used in each class and 2) higher content complexity tasks used in each class.

Students’ prior knowledge. All students from participating biology classrooms completed the 31-item factual knowledge test before and after the teaching unit ‘blood and circulatory system’. This instrument measured students’ factual knowledge about ‘blood and circulatory system’ (Wadouh, 2008). This test consisted of multiple choice items (N =25), match the terms (N =1), draw and label diagram (N = 1) and filling the gaps (N =4). Student pre-unit performance in this test was used as a covariate in the study presented here.

Students’ motivation and interest to learn biology. Questionnaire developed by Wild, Hofer and Pekrun (2001) and adapted for the subject biology was completed by students from all participating biology classrooms in the beginning of the teaching unit ‘blood and circulatory system’. It consisted of four scales: Interest in subject biology (N = 3 items, $\alpha = 0.89$), Interest in subject related activities (N = 3 items, $\alpha = 0.56$), Intrinsic Motivation (N = 7 items, $\alpha = 0.83$) and Extrinsic Motivation (N = 9 items, $\alpha = 0.54$). Students’ rated their agreement on four-point likert scale ranging from 0 (not true) to +3 (true). Four sub-scales of this instrument showed good reliability (Cortina, 1993; Wadouh, 2008). Z- standardized values of individual student scores on all four sub-scales of this instrument were used to calculate the four motivation and interest related variables: 1) *students*’ *extrinsic motivation*, 2) *students*’ *intrinsic motivation*, 3) *students*’ *interest in subject biology* and 4) *students*’ *interest in biology activities*.

Above described variables were used as control variates to examine the influence of instructional features (here: *challenging tasks*) on students’ cognitive knowledge structure. This data was also used in another study to examine the influence of *teaching interconnected complex domain content* on *students’ cognitive knowledge structure* (Wadouh et al., 2014).

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Data Analysis Using Linear Multilevel Modeling

This study investigated the influence of class level predictors *high level cognitive processing tasks* & *higher content complexity tasks* on *students' cognitive knowledge structure*. Additionally, *students' prior knowledge*, *students' extrinsic motivation*, *students' intrinsic motivation*, *students*' *interest in subject biology* and *students*' *interest in biology activities* were used as covariates, while examining the influence of '*using challenging tasks*' on *students' cognitive knowledge structure*. As explained earlier, this study collected hierarchically – nested data, and thus linear multilevel modeling in SPSS was used to test the hypotheses formulated for this study (Field, 2009; Heck, Thomas & Tabata, 2013).

Results

Results of this study are divided in two parts. The first part presents descriptive statistics pertaining to the independent variables, dependent variables and control covariates investigated for this study. The second part describes findings from linear multilevel modeling in SPSS where *high level cognitive processing tasks & higher content complexity tasks* were used as class level predictors to study to investigate their influence on *students' cognitive knowledge structure.*

Descriptive Statistics

Videotaped lessons. All 38 videotaped lessons were first coded for the frequency of new teacher initiated tasks. We found 1704 instances where teacher initiated new tasks during classroom discourse (min = 16; max = 88; SD = 18.42). Later, each *new teacher initiated task* was coded for their level of cognitive processing and complexity of task content. 366 *high level cognitive processing tasks* (min = 0; max = 32, SD = 6.63) were found in 38 investigated biology lessons. Higher level cognitive processing tasks involved deeper information processing situations like justifying, formulating hypotheses, interpreting, reflecting and evaluating (See Table 4). Furthermore, 614 *higher content complexity tasks* (min = 0; max = 37, SD = 9.50) were found in biology lessons. Higher content complexity tasks involved linking and conceptual level content (See Table 5).

Students' prior knowledge test. 31 item testing instrument measuring students' knowledge related to the topic 'blood and circulatory system' exhibited satisfactory internal consistency (α =0.72). Mean task difficulty was 0.64 (min = 0.18; max = 0.89) and selectivity ranged from 0.04 to 0.40 (Wadouh, 2008). Student performance in this test, before the teaching unit 'blood and circulatory system' was used as a control variable, while investigating the influence of *challenging tasks* on students' performance in the concept mapping exercise.

Findings from Linear Multilevel Modeling in SPSS

As explained earlier, data collected for this study included both class level and individual student level variables. We also calculated the intra-class correlation (ICC), which indicates how students from various classes differed in their performance in the concept mapping exercise. When *students' cognitive knowledge structure* (i.e. aggregate student performance in concept mapping) was used to generate the 'Restricted Maximum Null Model', ICC value calculated was about 0.070. This means that 7.0% variance in *students' cognitive knowledge structure* was located at

Table 6

Maximum likelihood random intercept models for 'High level cognitive processing tasks'

Dependent variable – Students Knowledge Structure (SKS)						
Predictors	Model 1 (Model 1SKS)		Model 2 (Model 2SKS)		Model 3### (Model 3SKS)	
	Estimate		Estimate		Estimate	
		SE	ß	SE	ß	SE
Intercepts						
Class-level						
High level cognitive processing tasks	0.07**	0.03	0.07*	0.02	0.07**	0.02
Individual-level						
Pre-knowledge			0.01**	0.001	0.01**	0.001
Interest in subject activities					-0.08	0.20
BIC	3666.15		3435.08		3432.89	
(ML)	(3639.83)		(3402.44)		(3393.74)	

Note: Maximum likelihood (ML) & Schwartz´s Bayesian Criterion/ Bayesian Information Criterion (BIC) were used for model selection.
ß = SPSS regression weights (Estimate of fixed effects); SE=standard error for estimates of fixed effects
****p ≤ 0.005; **p ≤ 0.01; *p ≤ 0.05; +p ≤ 0.10.*
###Best fit model (Based on BIC and Maximum Likelihood comparison.)
All Individual level variables were grand mean centered before creating likelihood models
Dependent variable – students' knowledge structure was the composite variable, calculated by adding the z-standardized values for 1) number of concept maps drawn, 2) number of total relations drawn with legible labels, 3) number of relations with technically correct explanations; 4) depth of description of relations drawn between two terms.

class level. However, as data were hierarchically nested, it warranted the use of multilevel modeling to examine the correlations proposed in hypotheses.

Models showing influence of high level cognitive processing tasks on students' cognitive knowledge structure. To explore the influence of class level predictor *high level* *cognitive processing tasks* on outcome variable *students' cognitive knowledge structure*, we generated various 'Maximum Likelihood Random Intercept Models'. Initial model (See Model 1: Table 6) was created with *high level cognitive processing tasks* as a class level predictor of *students' cognitive knowledge structure*. Later on, covariates like *students' prior knowledge*, *students' extrinsic motivation, students' intrinsic motivation, students' interest in the subject biology*, *students' interest in subject related activities* were gradually introduced as grand-mean centered predictors. "Maximum Likelihood (ML)" and "Bayesian Information Criterion (BIC)" estimates for these models were compared to choose the best model that predicted *students' cognitive knowledge structur*e. Thus, the final model was chosen where ML and BIC estimates showed a significant decline (Field, 2009, p. 753) (See Model 2 & 3: Table 6). BIC value of this model (See Model 3: Table 6) was 4421. 42 and this estimate (BIC) did not decline further, when additional student level covariates were added. The final model (See Model 3: Table 6) depicted that *students' prior knowledge* related to blood and circulatory had significant, however very low impact on *students' cognitive knowledge structure* ($\beta = 0.01$). Besides that, *students' interest in biology activities* improved the ML and BIC estimates (See Model 2,3: Table 6) but did not correlate with *students' cognitive knowledge structure*, while *high level cognitive processing tasks* showed a moderate impact on *students' cognitive knowledge structure* ($\beta = 0.07$). Here, β represents the partial regression coefficient' or unstandardized regression estimates, presented as 'estimates of fixed effects' in SPSS (See Model 1, 2 & 3: Table 6) (Bring, 1994; Heck et al., 2013). In the end, it is important to note that several models were created in SPSS with covariates related to students' intrinsic motivation, extrinsic motivation and interest in biology. However, we did not report these models as the covariates neither improved the ML and BIC values nor significantly correlated with *students' cognitive knowledge structure*.

Multilevel models showing influence of higher content complexity tasks on students' cognitive knowledge structure. In order to explore the influence of class level predictor *higher complexity tasks* on student outcome variable - *students' cognitive knowledge structure*, we generated various 'Maximum Likelihood Random Intercept Models'. The initial model (See Model 1: Table 7) was created with *higher content complexity tasks* as a class level predictor of *students' cognitive knowledge structure*. Later on, student level covariates were gradually added. However, these maximum likelihood random intercept models did not show any significant influence of class level predictor *higher complexity tasks* on *students' cognitive knowledge structure*.

Table 7

Maximum likelihood random intercept models for 'Higher content complexity tasks'

Dependent variable – Students' Knowledge Structure (SKS)		
Predictors	Model 1 (Model 1SKS)	
	ß	SE
Intercepts		
Class-level		
Higher content complexity tasks	.01	.02
Individual-level		
Pre-knowledge		
Interest in subject		
Interest in subject activities FVV		
BIC	3673.59	
(ML)	(3647.27)	

Note: Maximum likelihood (ML) & Schwartz´s Bayesian Criterion/ Bayesian Information Criterion (BIC) were used for model selection.
ß = SPSS regression weights (Estimate of fixed effects); SE=standard error for estimates of fixed effects
###Best fit model (Based on BIC and Maximum Likelihood comparison.)
All Individual level variables were grand mean centered before creating likelihood models.
Dependent variable – students' knowledge structure was calculated as a sum of z-standardized values for 1) number of concept maps drawn, 2) number of total relations drawn with legible labels, 3) number of relations with technically correct explanations; 4) depth of description of relations drawn between two terms.

Discussion

This section will first endeavor to relate study aims with key findings described in the previous section. Later, we will discuss methodological and generalizability concerns pertaining to this study. Last, this section will briefly describe key implications of the results obtained and present perspectives about the way ahead for future studies.

First, this study successfully used the three-step coding manual to objectively and reliably identify *high level cognitive processing tasks* (Anderson & Krathwohl, 2001; Blooms, 1972; Blooms Taxonomy, n.d.; Krathwohl, 2002) and *higher content complexity tasks* (Nachreiner et al., 2015; Hiebert et al., 2003; Jacobs et al., 2003, 2006; Wadouh et al., 2014) used in biology lesson videos. However, we assumed that '*complexity of task content*' and '*cognitive processing level of tasks'* are two defining characteristics of *challenging tasks* (Blumenfeld & Meece, 1988).

Furthermore, this study confirmed the first hypothesis, which proposed that *high level cognitive processing tasks* will positively predict *students' cognitive knowledge structure* in biology (Brown, 1994; Klieme & Bos, 2000; Lipowsky et al., 2009; Stein & Lane, 1996). These results are in line with findings from a similar investigation using grade 6 biology lessons that found a positive influence of *high level cognitive processing tasks* in biology classrooms on students' factual knowledge and structural knowledge (Förtsch, 2015b).

In this regard, we used student level covariates related to prior knowledge, motivation and interest, while constructing linear multilevel models. Comparing ML and BIC values for these models showed a significant but low impact of *students' prior knowledge* on their performance in concept mapping. Students' prior knowledge related to the topic usually consists of fact level information and pre-concepts, while concept mapping requires students to describe links or conceptual relation between any two terms. This could be one reason for the minimal impact of prior knowledge on performance in concept mapping. Moreover, *students' interest in biology activities* improved the ML and BIC values and hence was retained in the final model (Field, 2009, p. 753). However, *students' interest in biology activities* along with other interest and motivation variables did not correlate with *students' cognitive knowledge structure*. One reason for such findings could be the way teaching lessons were implemented. As shown in the descriptive section, teachers rarely used challenging tasks during classroom discourse and thus teacher-student interactions could not activate students to benefit from their individual interest and motivation attitudes to acquire in depth understanding of the topic being taught.

Furthermore, we could not confirm the second hypothesis which states that *higher content complexity tasks* will positively influence *students' cognitive knowledge structure* in biology classrooms (Jacobs, 2003). Our investigation used a three-level coding manual for coding content complexity: 1) Tasks at fact level; 2) Tasks at linking level; 3) Tasks at conceptual level for identifying *higher content complexity tasks* in biology lessons (See Table 5). Here, descriptive statistics shows that very few *conceptual level tasks* were used by teachers during the classroom discourse. This could be one reason why our statistical analysis could not find a correlation between *higher content complexity tasks* and *students' cognitive knowledge structure*. Future studies in this regard could include interventions where teachers are trained/ encouraged to use *tasks involving conceptual level content* to meaningfully examine the correlation between use of *higher content complexity tasks* and *students' cognitive knowledge structure*.

Limitations

Data pertaining to this study were collected from the German state of North-Rhine Westphalia. As participation in this study was not compulsory, we collected data from schools and biology teachers who gave their consent in the beginning of the study. Such a strategy of data collection could present concerns regarding the generalizability of results obtained. Nevertheless, it must be noted that empirical studies that use external observer ratings for analysing data usually collect one or few lessons per teacher (Praetorius et al., 2014). Researchers, in this regard have argued that instructional competence does not change in a short time and hence daily teaching practice will show sufficient stability, especially in the absence of planned interventions or training.

Furthermore, due to the resource and time constraints, the presented study videotaped one lesson per teacher (N = 47 teachers) about the topic 'blood and circulatory system'. As mentioned earlier, collecting data related to one common topic helped 1) standardize the content 2) facilitated comparison of instructional practices and 3) helped collect pre-post assessment data related to the topic 'blood and circulatory system' to examine the correlations (Hugener et al., 2009). However, the limited sample size and use of lessons pertaining to one topic could again raise concerns about the generalizability of results presented. Future studies in this regard could videotape multiple lessons related to two or more topics to triangulate data and enhance the validity and generalizability of results obtained (Bush, 2012; Mathison, 1988).

To conclude, findings presented here contribute to the existing attempts towards understanding effective science instruction. These results could provide significant ideas for teacher trainers and in-service and future teachers to refine their practice and facilitate student understanding about a given topic. These results and ensuing discussions would be significantly informative for designing video based in-service teacher training programs for enhancing teaching effectiveness in science, especially biology.

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3.2. Publication II

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Teachers' Use of Focus Questions in German Biology Classrooms: A Video-Based Naturalistic Study

Abstract

This study investigated the effects of teachers' use of *focus questions* on students' knowledge structures and classroom teaching-learning process by re-analyzing selected data from a quasi-experimental pre-post video study (Wadouh, 2007). Focus questions are content-related anchoring questions highlighting the key content taught in individual lessons (Forbes & Davis, 2009). In Wadouh' study, students answered a knowledge test before and after the lesson on 'Blood and the circulatory system' and one lesson per teacher was videotaped to investigate teaching practices in grade 9 biology classrooms. Students also completed a post-unit concept mapping exercise and a motivation-interest questionnaire. In this study, 30 lesson videos selected from 47 were re-analyzed for teachers' use of focus questions—no focus questions, non-specific or simple focus questions, and specific and challenging focus questions. Individual students' scores in the concept mapping exercise were aggregated as *students' topic-related knowledge structure*. Multilevel analyses revealed a significant positive effect of teachers' use of *specific and challenging focus questions* on students' topic-related knowledge structure. Furthermore, a comparative case analysis of the classroom teaching-learning process was conducted in four lessons where teachers used specific and challenging focus questions in two of the lessons and non-specific or simple focus questions in the other two lessons. The findings indicate that *specific and challenging focus questions* anchored lessons on students' co-construction of scientific explanations by activating their pre-instructional ideas, whereas *non-specific or simple focus questions* anchored lessons on their accumulation of canonical scientific knowledge. This study's limitations and implications for teacher education reform are discussed.

Keywords: *Anchoring questions; Biology teaching*; *Focus questions*; *Video studies*

General Introduction

Seidel and Shavelson (2007) emphasized in their meta-analysis that general teaching components such as teacher-student relationship or classroom management cannot fully describe the teaching effectiveness in specific domains like physics, chemistry, or biology. Since then, empirical studies have focused on analyzing the effects of domain-specific teaching components such as the use of challenging questions, explanation-oriented content, authentic experimental data, and models on student-level outcomes (e.g., Fischer, Labudde, Neumann, & Viiri, 2014; Hugener et al., 2009; Lipowsky et al., 2009). However, there are few studies investigating the effect of *teachers' use of focus questions* on student learning and discourse activities in biology classrooms. *Focus questions* are content-related 'anchoring questions' that help highlight the main content being taught in individual lessons (Forbes & Davis, 2010; Schwille, Numedahl, Kruse, & Hvidsten, 2011). Forbes and Davis described 'anchoring questions' as highly visible tools that: 1) direct lesson activities toward developing the most important content, and 2) help students see the connections between various classroom teaching-learning experiences. In that sense, focus questions can be viewed as advanced organizers or pre-instructional guiding questions that: 1) help clarify the aims of a lesson, 2) activate students' preconceptions and pre-instructional ideas about a topic, and 3) facilitate students in organizing and making sense of the new information presented by the teacher (Ausubel, 1960; Joyce, Weil, & Calhoun, 2003; Mayer, 2003).

This naturalistic video study aimed to ascertain the extent to which the instructional use of focus questions could lead to increased elaboration and refinement of *students' topic-related knowledge structure* or *schema* measured using a concept mapping exercise. Moreover, a comparative case analysis was employed to investigate the effect of teachers' use of focus questions on classroom teaching-learning process or to determine the way focus questions were formulated, the complexity of content taught in lessons, and student engagement in the knowledge construction process.

Focus Questions as Anchoring Questions in Science Classrooms

Questions are important discursive tools that facilitate teacher-student interactions in science classrooms. Questions help teachers and students negotiate what is meaningful by discussing and making sense of the irregularities or contradictions that often drive meaningful learning (Forbes & Davis, 2010). In this study, the term *meaningful learning* implies the acquisition of new knowledge in ways in which it can be retrieved for later use in new contexts or problem scenarios (Mayer, 2002). Questions are very frequently used to engage students with a new topic, both in traditional teacher-centered expository classrooms and student-centered exploratory classrooms (Forbes & Davis, 2010; Mutai, Changeiywo, & Okere, 2014). Teacher-centered expository classrooms often emphasize the absoluteness of the content being taught and thus use the ‘who-what-where’ type description-oriented questions to engage students in the teaching-learning process. Such teacher-centered discourses limit students’ sense-making and can negatively impact their meaningful learning of the content being taught (Lemke, 1990; Morrison & Lederman, 2003). On the other hand, constructivist student-centered discourses emphasize active and dialogic student engagement in the new knowledge construction process. Such lessons are driven by ‘how-why’ type of anchoring questions that help direct the teaching-learning activities toward *co-constructing scientific explanations* about the topic being taught (Authors, 2016; Braaten & Windschitl, 2011; Forbes & Davis, 2010; Kelly & Crawford, 1997; Osborne & Patterson, 2011; Reiser, 2004). Forbes and Davis emphasize that teachers’ use of *explanation-driven anchoring questions* (i.e., ‘how-why’ type of questions or ‘problem scenarios’) can activate students’ pre-instructional ideas and facilitate active-dialogic student engagement in the sense-making process. Moreover, such questions can direct the teaching-learning activities toward constructing *causal-mechanistic explanations* about the topic being taught.

Forbes and Davis (2010) described two types of anchoring questions used within the framework of project-based science units: *driving questions and investigation questions*. *Driving questions* are explanation-driven, open-ended questions, and are presented at the beginning of science units, whereas *investigation questions* are ‘how or why’ type of questions, presented at the beginning of the individual science lessons. A similar two-tier level of questions was described by McTighe and Wiggins (2013) who used the terms ‘essential questions’ or overarching questions and ‘daily questions’ or opening questions while planning curriculum units and individual lessons using the ‘understanding by design (UBD)’ framework. Here, the term ‘essential questions’ refers to the unit-level questions formulated around the key concepts, theories, or problems being addressed in the lessons. Essential questions reflect the key principles or inquiries guiding a domain, and thus, such questions do not focus on one specific topic or theme being taught in the lesson. On the other hand, the term ‘daily questions’ refers to hooks or opening questions that help engage students with the specific content being addressed in the lesson. In that context, the term 'focus questions' can be described as content-related investigation questions or daily questions presented at the beginning of individual science lessons.

Focus questions can also be thought of as advanced organizers that help introduce the lesson topic and collect students' prior knowledge and pre-instructional ideas about the content or concepts being presented in a particular lesson. Furthermore, teachers' use of focus questions as introductory tools or advanced organizers can: 1) steer the teaching-learning activities to develop the most important content, 2) highlight connections among various teaching-learning activities and conceptual ideas in the lesson discourse, and 3) help learners anticipate and organize new knowledge taught in the lesson (Ausubel, 1960).

A review of the literature about anchoring questions (i.e., driving questions, investigation question, essential questions, and focus questions) suggests that explanation-driven anchoring questions: 1) integrate the most important content (i.e., science phenomena or conceptual ideas) being taught in lessons; 2) include terms and/or contexts that make sense to students; 3) can be answered within the time frame of individual science lessons or units; and 4) encourage students to explore the conceptual level content (i.e., interconnections between facts, principles, or disciplinary core ideas) that helps construct a causal-mechanistic explanation for a phenomenon, life process or regularity being investigated in a lesson (Forbes & Davis, 2010; Krajcik & Mamlok-Naaman, 2006; Schwille et al., 2011; Schornborn & Bogeholz, 2009; Authors, 2014). In this study, characteristics of focus questions were used as a guide to categorize focus questions into two types: 1) *specific and challenging focus questions* and 2) *non-specific or simple focus questions.*

1) Specific and challenging focus questions are explanation-driven 'how-why' type of questions or real-life problems formulated around one or a few specific biology phenomena, events, regularities, or life processes in the lessons. Such questions, formulated using simple and easily understandable terms or real-life contexts, direct the lessons toward exploring interconnections between facts, principles, and disciplinary core ideas and help students develop a scientific explanation for a particular phenomenon, event, or life process. These questions can be used to anchor the *conceptual science storylines*, where teachers along with students are engaged in co-constructing causal-mechanistic explanations about one or a few specific biology phenomena, events, regularities, or life processes (Hanuscin et al., 2016; Reiser, 2013; Roth et al., 2006; Schwille et al., 2011). One example is the biology phenomenon 'blood transfusion and agglutination' and the specific and challenging focus question is 'Think like a scientist from earlier times and ponder why blood clumps during transfusion in some cases and not in other cases.'

2) Non-specific or simple focus questions: Non-specific focus questions are not specifically linked to the most important content (i.e., biology phenomenon, event, or life process) being developed in the lessons and such these questions do not highlight the purpose or key content in the lesson. *Simple focus questions* refer to 'what-where-who-when' type of descriptive questions that require students to accumulate, recall, or paraphrase the canonical scientific knowledge about a topic. Neither non-specific nor simple focus questions direct the lesson toward constructing causal-mechanistic explanations and hence can deter active student engagement in the sense making process. One example seen in the lesson on 'blood and its components' was: How is it that blood cannot be synthesized artificially? Another example was seen in the lesson dealing with 'blood transfusion and agglutination' where the focus question was: What is agglutination? What does it mean, when we say the blood types do not match?

Teachers' choice of specific and challenging versus non-specific or simple focus questions reflects on their use of pedagogical content knowledge (PCK) in choosing specific learning strategies for teaching the subject matter. Shulman (1986) described PCK as "ways of representing and formulating the subject that makes it comprehensible to others" (p. 9). PCK can be identified in the choice of specific content and instructional strategies used to teach the specific subject matter. In this regard, teachers' use of specific and challenging focus questions represents individuals' emphasis on presenting the interconnections between facts, principles, and disciplinary core ideas to help students acquire a deeper understanding of the subject matter. Moreover, as described earlier in this article, teachers' use of specific and challenging focus questions activates students' prior knowledge and ideas, which can then be manipulated to construct scientifically acceptable knowledge. On the other hand, teachers' use of non-specific or simple focus questions exhibits their emphasis on presenting canonical scientific knowledge about the domain (Forbes & Davis, 2010).

Cognitive Schemas or Knowledge Structures

The Schema Theory suggests that learners organize new knowledge in the form of *schemas or knowledge structures,* which are usually stored in the long-term memory (Ausubel, 2012; Chi, Glaser, & Rees, 1982). As opposed to the discrete knowledge of facts, functions, or features; schemas or knowledge structures consist of interlinked information about any particular topic. Schemas or knowledge structures represent highly structured units of information that can be processed as a single unit in the working memory (Cook, 2006). This organization of knowledge structures minimizes the load on the working memory, which can then be used to process the new incoming information or learning tasks. Using this framework, learning can be described as a continuous process of enriching, modifying, and refining learners' existing *schemas* or *knowledge structures* about the topic or domain (Novak, 2002; Voisniadou & Brewer, 1987).

Elaborate and refined knowledge structures can be considered important indicators of individuals' topic- or domain-related expertise (Gruber & Mandl, 1996; Authors, 2014). In this study, we endeavored to investigate how teachers' use of specific and challenging versus non-specific or simple focus questions enhanced *students' topic-related knowledge structure*. A teachers' use of specific and challenging focus questions anchors classroom teaching-learning activities on *co-constructing scientific explanations*. Teacher-student interactions are, therefore, directed toward exploring the interrelations between facts, principles, and disciplinary core ideas. Such explanation-driven questions can extend and refine students' existing knowledge structures about a particular topic. On the other hand, teachers' use of non-specific or simple focus questions direct the lesson toward exploring seemingly isolated facts about a particular topic. Hence, such questions may influence students' existing topic-related knowledge structures.

Concept Mapping

Concept maps consist of a set of linkages or propositions that explain the relation between two or more concepts. Here, the term 'concept' implies key domain-specific terms used to label the perceived regularities, events, or observable phenomena (Novak, 1990). The quantity and quality of these propositions in a particular concept map can depict a learner's 'knowledge structure' about any given topic or domain. Moreover, the number of discrete or disconnected 'concept maps' drawn indicate the extent to which learners can relate various concepts in the lessons. This study used student-drawn concept maps to measure their knowledge structure about the topic 'Blood and the circulatory system.'

Authors (2014) developed a quantitative scoring method to evaluate concept maps drawn by students in terms of five variables: 1) total number of linkages or propositions drawn, 2) number of cross-linkages drawn (i.e., connections drawn between terms from the topic ‘Blood and the circulatory system’ and other topics such as ‘respiration’ or ‘digestion'), 3) number of discrete or disconnected concept maps drawn, 4) number of correctly explained linkages, and 5) number of linkages described using the conceptual level content. Using the concept mapping variables, Authors (2014) analyzed the effects of *teaching interconnected domain content* on students’ cognitive knowledge structure; and on the basis of the results of the analysis of these variables described here, Authors (2016) calculated an aggregated score for individual students, which was used to determine the correlation between *teachers’ use of challenging tasks* and *students’ topic-related knowledge structure*. In this study, these aggregated individual students’ scores were used to quantify how teachers’ use of focus questions influenced students’ topic-related knowledge structure.

Students’ Prior Knowledge

Learning is an active and ongoing process of acquiring new knowledge and linking it with existing knowledge. Such a process can help learners expand, modify, and refine their knowledge structure about any given topic (Novak, 2002; Authors, 2014). Fraser, Walberg, Welch, and Hattie (1987), and Johnson and Lawson (1998) showed that the availability of relevant prior knowledge is an important predictor for new knowledge acquisition in the classroom. In this study, students’ prior knowledge about the topic ‘Blood and the circulatory system’ was used as a covariate.

Interest in Learning Biology

Interest can be defined as an individual’s engagement with a particular topic or activity. Therefore, interest can be measured by evaluating the relation between an individual and a specific task or content area (Prenzel, 1988; Krapp, 1999). Within the scope of biology, person-object interest could be defined as students’ readiness to engage with biology content and biology-related learning activities in the classroom discourse (Krapp, Hidi, & Renninger, 1992; Authors, 2014). Several empirical studies identified a positive correlation between students’ interest and their learning success (e.g., Prenzel, 1988; Schiefele & Schreyer, 1992). This study used control variables such as students’ interest in the subject biology and students’ interest in biology-related activities, while determining the extent to which teachers’ use of focus questions led to increased elaboration and refinement of students’ topic-related knowledge structure or schema.

Quantitative Segment

Research Question and Hypotheses:

This observational video study investigated how teachers' use of focus questions in German biology classrooms correlated with *students' topic-related knowledge structure.* Student-level variables—prior knowledge, interest in biology, and interest in biology-related activities—were used as covariates.

1. What impact do teachers' use of focus questions have on students' knowledge structure measured using a post-unit concept mapping exercise?

   Hypothesis 1a: Teachers' use of *specific and challenging focus questions* to have positive effects on *students' topic-related knowledge structure.*

   Hypothesis 1b: Teachers' use of *non-specific or simple focus questions* to have no effect on *students' topic-related knowledge structure.*

Qualitative Case Study

Research Question and Hypotheses:

2. How do the teachers' use of *specific and challenging focus questions* compare with the *non-specific or simple focus questions* affect the classroom teaching-learning process?

   Hypothesis 2a: Teachers' use of *specific and challenging focus questions* will activate students' pre-instructional ideas and direct the lesson activities toward negotiating meaning and co-constructing scientific explanations about a phenomenon, regularity, or event.

   Hypothesis 2b: Teachers' use of *non-specific or simple focus questions* will direct the lesson activities and ensuing discussions toward presenting and reviewing the canonical scientific knowledge about the topic being taught.

Method

This re-analysis and comparative case study of the video-based empirical data used qualitative and quantitative approaches to answer the research questions formulated above. First, the quantitative correlational analysis was used to investigate the effects of teachers' use of focus questions on students' topic-related knowledge structure. Second, the comparative case analysis was used to investigate four lessons, where two teachers used specific and challenging focus questions in two of the lessons and another two teachers used non-specific and simple focus questions in the other two lessons.

Design for Data Collection

In this study, we re-analyzed the lesson videos and other data we selected from the previous video study of the Gymansium (Grade 9) schools of Germany (Jatzwauk, 2007; Wadouh, 2007; Authors, 2014). The initial video study used a quasi-experimental pre-post design. The following three-step data collection process was used in the video study (Wadouh, 2007; Jatzwauk, 2007): 1) students answered the motivation-interest in biology questionnaire and prior knowledge test (N = 31 items) on the topic 'Blood and the circulatory system,' 2) one lesson per class (N = 47 classrooms/teachers) was videotaped, 3) students answered a post-unit knowledge test (N = 31 items) and completed a concept-mapping exercise on the topic 'Blood and the circulatory system.'

Participants

In the original video study (Wadouh, 2007; Jatzwauk, 2007), 47 biology lesson videos (approximately 45 min each) on the topic 'Blood and the circulatory system' were recorded in randomly selected grade 9 classrooms. Teachers were informed about the broader aims of this study. That is, the lesson videos would be used to explore the alternative teaching practices used in the German secondary biology classrooms. However, teachers were not provided with specific information about the domain-specific components (e.g., use of focus questions, student engagement in the classroom teaching-learning process, complexity of content) being correlated with the student performance. This was to ensure participating teachers used their usual typical strategies to plan and implement lessons pertaining to the teaching unit 'Blood and the circulatory system.' Also, it is important to note that the German teacher preparation programs do not explicitly inform or train teachers in formulating and integrating driving questions in a lesson, although these teacher preparation approaches do emphasize the ideas of context-oriented and problem-oriented learning. It is hence a plausible assumption that teachers develop the use of focus-questions-oriented teaching from their experience of teaching secondary biology content.

The 47 teachers who participated in the data collected in the video study were on average 46 years old (min = 28, max = 60, SD = 10; N = 47) with 18 years of teaching experience (min = 1, max = 31, SD = 11; N = 47). In this study, we only investigated 30 of the 47 original videotapes lessons for which complete data set pertaining to the pre-post knowledge test and the concept mapping exercise were available. The average class size of these selected 30 videotaped lessons was 25.30 students (min = 20, max = 30). Moreover, there were 17 female teachers and 11 male teachers in the selected set of 30 teachers. Two teachers did not fill out the 'Teacher questionnaire'.

Instruments for Quantitative Analysis

Category system for video coding. We used a theoretically-devised coding scheme to identify teachers' use of focus questions in the 30 videotaped lessons (see Table 1). Video coding process involved careful viewing of the video of each of the entire lessons to identify one or more of the following events: 1) The teacher wrote the question on the board and asked students to present pre-instructional explanations; 2) The teacher initiated the question and announced it as the main question for the lesson, the main question for the discussion, or the central theme of the lesson; 3) The teacher repeated the question during the lesson to highlight the importance of the content being discussed. As well, the teacher-formulated focus questions were rated as either *specific and* challenging or *non-specific or simple* factual focus questions. One coder analyzed all the 30 videos for this study. The second coder viewed five out of the 30 videos to ascertain any bias and determine the inter-rater agreement for the coding. This was found to be initially 80% but after discussion 100% agreement was reached.

Table 1

Rating system for teachers' use of focus questions in biology videos

Category	Description	Example
No focus questions		*Lesson topic: Blood clumping and blood types* Teacher introduces the topic but does not present any central question for the lesson.
Teachers use of focus questions	Teacher or students formulate a question(s) and teacher uses key words (i.e., central theme/ main question/ investigation question/ that day's question) to highlight it as focus question for the lesson. OR Teacher or students formulate a question(s) and teacher 'writes it down' or 'repeats it' in the classroom discourse to highlight the main content being developed during the lesson.	
Specific and challenging focus questions	1. 'How-why' type of questions or real-life problems, formulated around the important biology phenomenon or conceptual ideas 2. Such questions require the use of complex domain-related content (e.g., interconnection between facts, principles or disciplinary core ideas). 3. These questions could be answered within the time frame of individual lesson.	1. Why do we need a circulatory system? How does the circulatory system help transport nutrients and waste substances in the human body? *Lesson topic: Transport of nutrients – waste substances in the body* 2. Think like a scientist from earlier times; How is it that blood clumps during transfusion in some cases and not in other cases?

		Lesson topic: Blood clumping and blood types
Simple factual level focus questions	1. 'What-where-who-when' type of questions that require students to recall or paraphrase scientifically acceptable factual knowledge.	1. What do you know generally about blood groups? *Lesson topic: Blood clumping and blood types* 2. What is adaptation? What are the climatic adaptations observed in desert plants? *Lesson topic: Climatic adaptations in plants*
Non-specific focus questions	1. Such question do not specifically highlight the most important content (i.e., biology phenomenon or conceptual ideas) being discussed in the lesson. 2. There are more than one possible answer or explanation for this question and the lesson activities focus on one specific answer.	1. How is it that we cannot synthesize blood artificially? *Lesson topic: Blood and its constituents* 2. Why did the child die after blood transfusion? *Lesson topic: Blood clumping and blood types*

Concept maps. The student scores on the concept mapping exercise in the video study (Wadouh, 2007) were used to evaluate *students' topic-related knowledge structure*. All students drew concept map(s) using the following 15 pre-determined seed concepts: 1) Heart, 2) Blood, 3) Blood cells, 4) Oxygen, 5) Muscles, 6) Circulation, 7) Nutrition, 8) Blood groups, 9) Blood donation, 10) Cellular respiration, 11) Movement, 12) Artery, 13) Energy, 14) Blood Pressure, and 15) Pathogens (Trowbridge & Wandersee, 1994). Handouts with step-by-step instructions on how to create concepts were distributed to the students. Some of the instructions included: 1) Arrows should be used to connect any two of the 15 terms provided; 2) Each arrow or connection should be explained using a few words or a sentence to indicate how these terms are related; 3) Students should use only the 15 terms mentioned above to construct their concept maps; 4) Each one of these 15 terms can be connected to any of the other 14 terms using single or multiple arrows. Using a category system based on frequency (e.g., Friege & Lind, 2000; Kinchin, 2011; Ruíz-Primo, 2000; Stoddart, Abrams, Gasper, & Canaday, 2000; Yin et al., 2005), Wadouh (2007) evaluated student concept maps in the video study. The following variables were evaluated: 1) total number of labelled propositions or linkages drawn; 2) number of disconnected concept maps drawn; 3) number of propositions with scientifically correct explanations; and 4) number of relations with deeper-conceptual-level explanations.

Pre- and post-unit achievement tests. In the video study (Wadouh, 2007), a 31- item factual knowledge test was answered by all participating students, before and after the teaching unit 'Blood and the circulatory system.' This instrument measured students' factual knowledge about the theme: Blood and the circulatory system. The test instrument included 25 multiple choice items, one matching terms item, one drawing and labelling related item and four fill-in-the-blanks items.

Interest questionnaire. Students' motivation and interest related questionnaire, developed by Wild, Hofer, and Pekrun (2001) and adapted for the subject biology, was completed by students of all 47 biology classrooms in the video study (Wadouh, 2007).

Quantitative Analysis Using Linear Multilevel Modeling

The quantitative part of this study looked at the influence of teachers' use of specific and challenging focus questions and non-specific or simple focus questions on students' knowledge structures in biology. This investigation used hierarchically nested data, where focus questions were observed as class-level variables, while the students' topic-related knowledge structure was evaluated at the student level. Moreover, student-level variables related to prior knowledge, interest, and motivation were used as covariates. Linear multilevel modeling in SPSS was used to investigate how teachers' use of focus questions influenced students' topic-related knowledge structure (Field, 2009, p.730).

Qualitative Analysis of Biology Lessons where Teachers Used Focus Questions

Qualitative segment of this study aimed to highlight key differences in the way focus questions anchored the new knowledge construction activities. We chose a purposive sampling approach and randomly chose four lessons, where teachers used *specific and challenging focus questions* in two of the lessons but *non-specific or simple fact level focus questions* in the other two lessons (Guarte & Barrios, 2006). Lesson videos, lesson transcripts, and lesson narratives (i.e., sequential description of the teaching-learning activities observed in the videos) were used for this comparative case analysis. First, the specific vignettes, where the teacher formulated the focus question from the lessons were analyzed. Later, the lesson activities were described to show key differences in 1) the complexity of new content developed, and 2) student engagement in the new knowledge construction process.

Results

Findings from this re-analysis and comparative case study are described in this section,

Descriptive Statistics

Students' topic-related knowledge structure. Inter-rater agreement for the analysis of the concept maps by two raters showed satisfactory values of Cohens' kappa coefficients (κ) (Wirtz & Caspar, 2002): κ = .93 for the total number of labelled propositions, κ = .61 for the number of disconnected concept maps drawn was, and κ = .73 for the number of relations with deeper-conceptual-level explanations (Wadouh, 2007).

Furthermore, principal component analysis (CPA) with varimax rotation was used to extract the possible independent components of the variable *students' topic-related knowledge structure* (Authors, 2016). The PCA matrix showed following loadings: 1) total number of labelled relations with scientifically acceptable explanations = .91; 2) total number of labelled relations = .89; 3) number of relations with deeper explanations = .68; and 4) number of concept maps or disconnected networks drawn = .65. As the factor analysis did not show any subscales, all factors were z-standardized and aggregated to form the student-level variable: *students' topic-related knowledge structure.* Authors (2016) then used this variable to investigate the effect of teachers' use of challenging tasks on student learning in biology. In this study, we used this aggregated variable to investigate the effect of focus questions on student learning.

Pre- and post-unit achievement tests. The test showed satisfactory internal consistency (α = .72). Task difficulty for this 31-item test was 0.64 (min = .18; max = .89). Students' pre-unit performance in this instrument was used to control for topic-related prior knowledge, while examining the hypothesis formulated in this study.

Interest questionnaire. Interest in biology was measured using two scales: Interest in Subject Biology (3 items, α = .89), Interest in Subject-related Activities (3 items, α = .56). The students rated their agreement to each item on a four-point Likert scale ranging from *0 (not true)* to *+3 (true)* (Authors, 2014; Authors, 2016). We used the data pertaining to the 'students' interest in biology' and 'students interest in biology-related activities' as covariates, while examining the hypotheses proposed for this study.

Teachers' use of focus questions. Nine out of 30 teachers used focus questions at the beginning of a lesson. Five teachers used the *specific and challenging focus questions,* the other four used the *non-specific or simple focus questions.*

Findings from Linear Multilevel Modeling

Maximum likelihood models were generated to investigate the hypotheses of the first research question. We calculated the intra-class correlation to determine the class-level variance in the students' topic-related knowledge structure. The Intra-Class Correlation (ICC) calculated for this study was 0.076. This means around 7.6% variance in *students' topic-related knowledge structure* was located at the class level. As the data of this study were hierarchically nested, that is, at the class and student levels, we conducted further analysis using the multilevel analysis procedure in SPSS to answer the first research question (Heck, Thomas, & Tabata, 2010).

What is the effect of teachers' use of specific and challenging focus questions on students' topic-related knowledge structure? An initial model (see Model 1 in Table 2) was created with a dummy coded class-level variable—specific and challenging focus questions as the class-level predictor of students' topic-related knowledge structure. Next, grand mean centred values of student-level covariates (i.e., students' prior knowledge, students interest in the subject biology, students' interest in subject-related activities) were gradually added until the maximum likelihood estimate (MLE) showed a significant decline (Field, 2009, p. 751) (see Models 2 and 3 in Table 2). The MLE value for the final model (see Model 3 in Table 2) was 1833.41 and this value did not decline significantly when the variable *students' interest in the subject biology* was included in the model. The final model (see Model 3 in Table 2) depicted a statistically significant impact of teachers' use of *specific and challenging focus questions* on students' topic-related knowledge structure (b = 0.36; p = .02). The final model indicated a significant but very low effect of students' prior knowledge on students' topic-related knowledge structure (b = 0.06; p = .000). Furthermore, the maximum likelihood model did not show any significant effect of students' interest in biology-related activities on students' topic-related knowledge structure. It is important to note here that b *d*enotes the unstandardized regression estimate, presented as the 'estimate of fixed effects' in SPSS (Field, 2009, p. 776).

Table 2
Maximum likelihood random intercept models for teachers use of specific and challenging focus questions

Dependent variable – Students' Topic-related Knowledge Structure (SKS)						
Predictors	Model 1 (Model 1SKS)		Model 2 (Model 2SKS)		Model 3### (Model 3SKS)	
	b	SE	*b*	SE	*b*	SE
Class level						
Specific and challenging focus questions	0.39*	0.15	0.36*	0.15	0.36*	0.15
Individual level						
Pre-knowledge			0.06***	0.01	0.06***	0.01
Interest in biology-related activities					-0.003	0.02
BIC	2036.85		1890.744		1872.50	
(MLE)	(2010.53)		(1858.10)		(1833.41)	

Note. Models were selected based on Maximum likelihood (ML) and Schwartz´s Bayesian Criterion/ Bayesian Information Criterion (BIC).
b = unstandardized regression weight (Estimate of fixed effects); SE=standard error
****p ≤ .005; **p ≤ .01; *p ≤ .05; +p ≤ .10.*
###Best fit model (Based on Maximum Likelihood comparison)
Class-level variable was dummy coded
All individual-level variables were grand mean centered before creating likelihood models
Students' topic-related knowledge structure was z-standardized

What is the effect of teachers' use of non-specific or simple focus questions on students' cognitive knowledge structure. Maximum Likelihood Random Intercept Models were created to explore the effect of the class-level predictor non-specific or simple focus questions on students' topic-related knowledge structure. The initial model (see Model 1 in Table 3) was created with non-specific or simple focus questions as a class-level predictor of students' topic-related knowledge structure. This model depicted a significant negative effect of non-specific or simple focus questions on students' topic-related knowledge structure (b = -0.36; p = .046). At this point, grand mean centred values of student-level variables, such as students' prior knowledge and students' interest in biology-related activities, were added to create additional models until the maximum likelihood estimates showed a significant decline. The final model (see Model 3 in Table

3) showed that there was no significant effect of teachers' use of non-specific or simple focus questions on students' topic-related knowledge structure.

These findings support our hypotheses 1a and 1b that: teachers' use of *specific and challenging focus questions* to have positive effects on *students' topic-related knowledge structure and* teachers' use of *non-specific or simple focus questions* to have no effect on *students' topic-related knowledge structure.*

Table 3
Maximum likelihood random intercept models for teachers use of non- specific or simple focus questions

	Dependent variable – Students' Topic-related Knowledge Structure (SKS)					
Predictors	Model 1 (Model 1SKS)		Model 2 (Model 2SKS)		Model 3### (Model 3SKS)	
	b	SE	*b*	SE	*b*	SE
Class level						
Non-specific or simple focus questions	-0.36*	.17	-0.25	0.18	-0.26	0.17
Individual level						
Pre-knowledge			0.06***	0.01	0.06***	0.01
Interest in biology-related activities					-0.001	0.02
BIC	2038.84		1894.36		1876.51	
(MLE)	(2012.53)		(1861.73)		(1837.42)	

Note. Models were selected based on Maximum Likelihood Estimates (MLE) & Schwartz´s Bayesian Criterion/ Bayesian Information Criterion (BIC).
b = unstandardized regression weight (Estimate of fixed effects); SE=standard error
$***p \leq .005$; $**p \leq .01$; $*p \leq .05$; $+p \leq .10$.
###Best fit model (Based on Maximum Likelihood comparison)
Class-level variable was dummy coded to investigate its effect on students' topic-related knowledge structure
All individual-level variables were grand mean centered before creating likelihood models
Dependent variable – students' topic-related knowledge structure was z-standardized

Key Findings from Qualitative Analysis

A comparative case analysis of discourse content from four lessons was conducted. Two lessons where specific and challenging focus questions, and two where teachers used non-specific or simple focus questions were compared. In line with the hypotheses of the qualitative segment for this study, the description below elaborates key differences in: 1) the way focus

Table 4

Comparative case analysis of lessons

Specific and challenging focus questions		Non-specific or simple focus questions	
Teacher 1: Sarah	Teacher 2: Julia	Teacher 3: Rihanna	Teacher 4: Shailey
The way focus questions were formulated			
Teacher presented a real-life problem: *'Think like scientists of earlier times when people did not know of blood types. Two thirds of the people who received the blood transfer died'. If you were a scientist, – what kind of question would you ask?'* Teacher collected students' questions and later formulated the focus question: *How is it that blood clumps, when it comes in contact with other blood?* Next, students presented their ideas and assumptions about when-how blood clumps.	Teacher presented a real-life problem*: Isabella is 15 years old and suddenly two people appear in her life and claim that they are her parents. Her actual parents also claim that they are her real parents. This threw her into a deep crisis.* Teacher initiated a discussion about: *We have the blood samples from all the parents and we know Isabella's blood group. How can we find her real parents?*	Teacher began the lesson by asking questions like: *Why do you think someone needs to know that (blood group)? Where it is important to know?* Later, teacher presented the focus question: *And today, we want to find out what is meant by that... blood doesn't match.*	Teacher showed objects such as stethoscope, red-cross symbol, syringe. Students related these items with the theme heart. Next, teacher presented the focus question: *What components are blood made of? What are some tasks that blood can perform and why can't blood be artificially synthesized?*
Exemplar lesson activities reflecting the complexity of content taught			
1. Students interpreted the results from the Landsteiner experiment about mixing blood of six different colleagues and analyzed data patterns to explore when blood clumps.	1. Students tested blood type of all the four potential parents. 2. Students used their knowledge	1. Teacher presented information about different types of blood types and antigen-antibodies related to different blood types.	1. Teacher presented a microscopic image of different blood cells to discuss different types of blood

2. Later, students used the information about antigens-antibodies present in different blood types and the lock-and key principle to present a scientific explanation for how/why blood clumps.	of blood types to explain who Isabella's real parents were.	2. Students were required to recall this information and tell the blood type of six participants from the Landsteiner experiment.	cells and their structure. 2. Later, students used information sheet about 'components of blood' to write a CV or personal profile for different types of blood cells.

questions were formulated; 2) the complexity of content taught in the lessons, and 3) student engagement in the new knowledge construction process.

The way focus questions were formulated. As can be seen in Table 4, Sarah and Julia presented a real-life scenario to highlight a phenomenon, event, regularity, or anomaly that should be investigated in the lesson. Next, both Sarah and Julia formulated the 'how-why' type of specific and challenging focus questions and initiated a discussion to solicit students' pre-instructional explanations about the specific phenomenon, event, or regularity that was highlighted in the real-life scenario. On the other hand, Rihanna and Shailey introduced the topic by asking recalling- or paraphrasing-oriented questions. Later, they presented a non-specific or simple focus question to highlight the key content in the lesson.

The complexity of content taught in the lessons. As described in Table 4, Sarah and Julia engaged their students in collecting and interpreting authentic data to construct causal-mechanistic explanations. The students explored the interconnections between facts and biology principles to make sense of the phenomenon, regularity, or anomaly being highlighted through the focus questions. On the other hand, Rihanna and Shailey focused on presenting canonical scientific explanation about the topic being taught. Sarah's class interpreted authentic data from the Landsteiner experiment to construct explanations for how/why the blood clumps. Similarly, Julia's class used the results from the blood tests and their understanding of genotypes/phenotypes to explain who Isabella's parents were. In contrast, Rihanna focused on presenting and reviewing the canonical scientific information about different blood types and blood clumping. Likewise, Shailey's class focused on exploring canonical information about the features and functions of different types of blood cells.

Student engagement in the new knowledge construction process. As can be seen in the Tables 4 and 5, Sarah used the specific and challenging focus question to activate students' prior conceptions and pre-instructional ideas. Later in her lesson, students were actively engaged in exploring how/when/why blood clumps based on the Landsteiner experiment about blood types. To elaborate this activity, Sarah required students to explore the interconnections between facts, concepts, and core ideas to explore the scientific explanation. On the other hand, Rihanna presented the canonical information about blood types and blood clumping. Later in her lesson, she required students to use this information and name the blood types of Landsteiner and colleagues. This required students to recall or paraphrase the important content taught in the lesson. To summarize, Sarah engaged students in negotiating ideas and co-constructing meaning, whereas Rihanna engaged students in exploring the canonical knowledge about blood types.

Table 5

Student engagement in the new knowledge construction process: Vignettes of teacher-student interaction

Teacher 1: Sarah	Teacher 3: Rihanna
T: Let's get back to the scientists from former times. What would you have done to find out why blood agglomerates? And when it agglomerates. Yes? *S: I would have taken blood from different people and would have mixed it up. Well. Just to try if and when it works and if I can see a result at the end.* *T: Yes, correct. It's a good approach. I write it down. Well: Mix blood of different people. Do you mean that way? This idea isn't bad, because it's actually the way how it was done. In 1901, there was a Mr. Landsteiner, he basically had the same procedure. He took blood from Dr Preschnik, Dr Schuli, Dr Decastello and of course from himself. He isolated the red blood cells of these different doctors and mixed them with their serum. What's the serum again?* *S: Eh, blood plasma. It's what comes out after the removal of the clotting substance.* *T: Right, exactly. Why does it make sense to use the serum, but not the blood plasma? What's the role of the clotting substance again?* *S: This way it doesn't agglomerate when it comes in contact with air.*	*T: Well. Here you can see this, this doctor Landsteiner. Of course, he didn't know anything about antibodies and antigens and so on. But he did… eh… An experiment. He participated in it as well. He took blood from 5 colleagues including himself. He separated the blood. He separated the blood cells, it's shown in the graph on the axis x. …and he separated the serum… You know that the blood cells possess antigens and the serum possesses antibodies. Then he mixed the serum with each type of blood cell. Here, it is written minus and plus… The minus stands for "nothing happened" and*

T: Right! Exactly. What does agglomerate when it comes in contact with air? In case we would have used the plasma instead of the serum?
S: The white blood cells or the leukocytes.
T: Leukocytes?
S: Well, the thrombocytes. (really quiet)
T: What does agglomerate and set free clotting substances?
S: Well, the thrombocytes.
T: The thrombocytes. They entail clotting substances. You're right. And then, it would agglomerate when it's on air. Well, he mixed the red blood cells, the erythrocytes, with the serum of the same people. And here, you can see what happened.
T: Have a look and describe what you see. What is striking in this experiment?
the plus stands for "clump". Alright. And now, I give you some time to think and you tell me what kind of blood groups they had.
T: I mean… There are 4 blood groups. You see six people. It means something will appear twice.
T: Can you find a solution? I know that it's not easy. It's really not easy.

General Discussion

Previous studies have documented the effectiveness of explanation-oriented anchoring questions in shifting the monologic teacher-centered interactions to dialogic student-centered discussions (Forbes & Davis, 2010; Krajcik & Mamlok-Naaman, 2006). However, these studies did not investigate how the teachers' use of anchoring questions influence student outcomes and lesson activities. Hence, this study investigated how the teachers' use of focus questions, one type of anchoring questions, in German biology classrooms influenced the students' topic-related knowledge structure and classroom teaching-learning process. In this study, the video-based lesson observations, and quantitative as well as qualitative data analysis approaches were used to investigate the teachers' use of focus questions.

First, the quantitative segment of this investigation analyzed the effect of teachers' use of *specific and challenging focus questions* versus *non-specific or simple focus questions* on students' knowledge structure. This correlational analysis showed statistically significant effect of teachers' use of specific and challenging focus questions on students' topic-related knowledge structure. Additionally, this correlational analysis showed that there was no statistically significant effect of teachers' use of non-specific or simple focus questions on students' topic-related knowledge structure. Theoretically-devised coding manual was used to observe and rate the biology lessons for teachers' use of focus questions. Here, we assumed that the raters could be adequately trained to observe high-inference instructional components like focus questions in biology classrooms. However, we would like to emphasize that the authors' decision was informed by the previous literature that advocated the use of video-based lesson analysis techniques in investigating the deeper features of classroom instruction (e.g., Hugener et al., 2009; Praetorius, Pauli, Reusser, Rakoczy, & Klieme, 2014). Moreover, the satisfactory inter-rater agreement between the two raters further validated the choice of video-based lesson observation method. Next, the correlational analysis used the linear multilevel modeling to address the clustered nature of the data. However, the inter-class correlation (ICC) calculated for the outcome variable students' topic-related knowledge structure was very low. Hence, we suggest that in further studies, researchers could use multiple student outcome measures to study the effect of teachers' use of focus questions on student learning, and the concept mapping used to evaluate students' topic-related knowledge could include additional guidelines and rubrics that encourage students to depict the deeper-level causal relations in their concept maps.

Second, the qualitative case analysis showed that teachers' use of specific and challenging focus questions not only anchored lesson activities on co-constructing causal-mechanistic explanations but also helped create a coherent conceptual science storyline (Forbes & Davis, 2010; Hanuscin et al., 2016). The analysis also revealed that these questions not only activated students existing conceptions or ideas about the topic, but also stimulated the active negotiation of meaning, which is a hallmark of student-centered dialogic classrooms. On the other hand, teachers' use of *non-specific or simple factual focus questions* anchored their lessons on accumulating facts or canonical scientific knowledge about the topic, but their students did not engage in negotiating and reviewing their pre-existing ideas about the topic. These findings are in line with the previous studies that suggest that the teacher-centered monologic teacher-student interactions are woven around what-who-when type factual questions (Forbes & Davis, 2010). As the hypotheses pertaining to the qualitative segment were tentatively formulated, this study used the purposive sampling approach and comparative case analysis to explore key differences in the classroom teaching-learning process. Although, this qualitative segment revealed key differences in the classroom teaching-learning process (e.g., how the focus questions were formulated, the complexity of content taught in the lessons, and the student engagement in the new knowledge construction process), focus questions could alter the teaching-learning process in a variety of ways that might not have been captures in this comparative case analysis.

Limitations

One limitation of this study was that very few teachers used focus questions in their lessons. Future studies should thus include a 'teacher intervention' component to develop and incorporate the use of focus questions in the biology lessons. Furthermore, we re-analyzed lesson videos and student-level data collected from schools and biology teachers who gave their voluntary consent. This could present concerns about whether the collected sample represents the actual population. Also, one lesson per teacher was analyzed. This could be of concern with regard to the generalizability of the findings. However, researchers have time and again argued that teachers' instructional practice remains stable and consistent in the absence of focused and long-term interventions (Praetorius et al., 2014). Thus, the empirical findings from this study can be reliably interpreted and implemented to enhance teaching effectiveness in biology classrooms.

Conclusions

This is the first study to our knowledge that investigated how the teachers' use of focus questions influenced students' topic-related knowledge structure and the classroom teaching-learning process. Findings obtained from the quantitative segment can inform the in-service and pre-service teacher preparation programs to support teachers in formulating and using the *specific and challenging focus questions.* The qualitative case analysis segment also offers authentic exemplars of how teachers could formulate and integrate focus questions in their classrooms. Moreover, this case analysis describes how German biology teachers used real-life scenarios, authentic data, and sense-making discussions to meaningfully engage students in answering the focus questions. We have already used this material to develop a pre-service biology teacher training course at our institute.

Future work should therefore include focused interventions to not only validate the effectiveness of focus questions but also investigate strategies that teachers use to meaningfully engage students in answering the focus questions.

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3.3. Manuscript I

Engaging Students in Constructing Scientific Explanations in Biology Classrooms: A lesson-design model

Submitted Manuscript in the
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Engaging Students in Constructing Scientific Explanations in Biology Classrooms: A lesson-design model

Constructing scientific explanations of natural phenomena is an important aim of science education. Explanation oriented science teaching approaches encourage learners to engage in sense making discussions and construct the causal mechanistic explanations of the phenomena under study (Authors 2017; Brigandt 2016). This article demonstrates a lesson-design model that guides biology teachers on how to integrate explanation oriented teaching in their everyday practice. The proposed model includes six phases: 1) presenting a hooking activity; 2) formulating a how-why type focus question; 3) constructing the initial causal story; 4) using authentic data, scientific facts, principles, and disciplinary core ideas to revise-refine the causal story; 5) discussing-rewriting the refined causal story; 6) applying the causal-mechanistic knowledge in a new context or problem scenario. An eleventh-grade lesson on the topic 'protein biosynthesis in cells' serves an example about how this model can be operationalized to design and implement explanation oriented biology lessons.

Keywords: *Causal explanations; Phenomena-based; Scientific explanations; Lesson planning; Biology teaching*

Introduction

The recent curriculum reforms in countries like Australia, Canada, Germany, and the United States emphasized that teachers should integrate core practices like scientific inquiry, explanation, and argumentation to teach interconnected and concept oriented science content in their everyday lessons (Council of Ministers of Education, Canada, 2013; Kultusministerkonferenz der Länder (KMK) 2005; National Curriculum Board (NCB) 2009a; National Research Council (NRC) 2012). Such scientific practices oriented teaching approaches not only orient learners towards the use of scientific methods but also ensure active student engagement in the knowledge construction process. Education researchers have thus developed a variety of lesson-design models that facilitate the meaningful integration of scientific practices such as inquiry and argumentation into the everyday science lessons (e.g. Bybee et al. 2006; Chen and Steenhoek 2014). However, there are hardly any models that guide teachers integrate the core practice of constructing causal scientific explanations into the everyday lessons. This article addresses this gap by demonstrating how scientific explanation construction can be used as a vehicle to plan and implement biology lessons.

In the sections below, we first elaborate the theoretical background underlying the process of constructing scientific explanations. Next, we describe the constructivist learning approach that often guides the development of student-centered, scientific practices oriented instructional models. Thereafter, we present the context in which the proposed lesson-design model was planned and tested. Later, we elaborate the six-phases of the proposed explanation oriented lesson design model. An eleventh-grade lesson on the topic ‘DNA and protein synthesis’ serves as an example of how explanation construction can be integrated into the biology lessons. Finally, we discuss the empirical findings from this collaborative lesson-design work and explain how the proposed model encompasses the three key aspects of cognitively activating instruction approach.

Explicating the process of constructing scientific explanations

Constructing scientific explanations is one of the core practices in science. Scientists very often engage in this practice to offer the causal-mechanistic account of the natural phenomena observed around us (Zimmermann 2007). Scientific explanation construction is thus seen as an important aspect of formal science education (Council of Ministers of Education, Canada, 2013; KMK, 2005; National Curriculum Board (NCB) 2009a; National Research Council (NRC) 2012). The next generation science standards advocate that engaging students in scientific practices fosters scientific sense-making, which implies that students engage in formulating and answering scientific appropriate questions, seeking causal-mechanistic explanations of phenomena, interpreting data tables, and writing-visually representing coherent causal accounts. In sum, this scientific practice catalyzes the transition from preconceptions to scientifically appropriate conceptual understandings (NGSS Lead States 2013). A review of the literature on constructing scientific causal explanations reveals that the process entails four key epistemic activities: observing a phenomenon and formulating a scientifically oriented question; analyzing - interpreting authentic data or texts to make causal inferences; developing causal-mechanistic explanations by connecting data with theoretical entities; and articulating coherent explanations of the phenomena (Authors 2017; Berland and Reiser 2009; Braaten and Windschitl 2011; Brigandt 2016; Delen and Krajcik 2015). These epistemic activities direct learners in developing evidence-based explanations, wherein learners employ their reasoning skills to elucidate the causal-mechanistic chain of events underlying a biological phenomenon (Brigandt 2016; Fischer et al. 2016; Teig and Scherer 2016; Zimmerman 2007). Adding to that, the process of formulating coherent explanations promotes the use of scientific principles (e.g. surface area, diffusion) and disciplinary core ideas (e.g. structure and function, variability and adaptation) as underlying domain-related ideas that help make sense of the subject matter ideas (e.g. experimental data on mixing blood from different individuals; the conceptual ideas of antigen, antibody, and antigen – antibody interactions; and the key-locker principle can be employed to explain how and why agglutination occurs in some cases and not in other cases) (see Figure 1) . To summarize, the explanation oriented science teaching practice cognitively activates learners to use the *reasoning skills* (i.e. formulate scientifically oriented questions, analyze and interpret data patterns, connect data patterns with theoretical entities to develop the causal chain of events) and develop evidence-based causal explanations of natural phenomena. Here, the term cognitive activation implies teachers' use of instructional practices that facilitate deeper processing of the information presented to acquire conceptual understanding of the subject matter (Kunter et al. 2007; Jordan et al. 2008).

Science education literature provides ample anecdotes about how teachers can meaningfully integrate this core practice in their everyday lessons (Authors 2017; Berland and Reiser 2009; Braaten and Windschitl 2011; Brigandt 2016; Delen and Krajcik 2015). However, explanation construction is often conflated with argumentation and thus is often difficult for teachers to trace the epistemic steps underlying this scientific practice and the way this practice could be meaningfully integrated in science lessons (Brigandt 2016). To address this problem, this article demonstrates a lesson-planning model that supports science teachers in planning and implementing explanation oriented biology lessons.

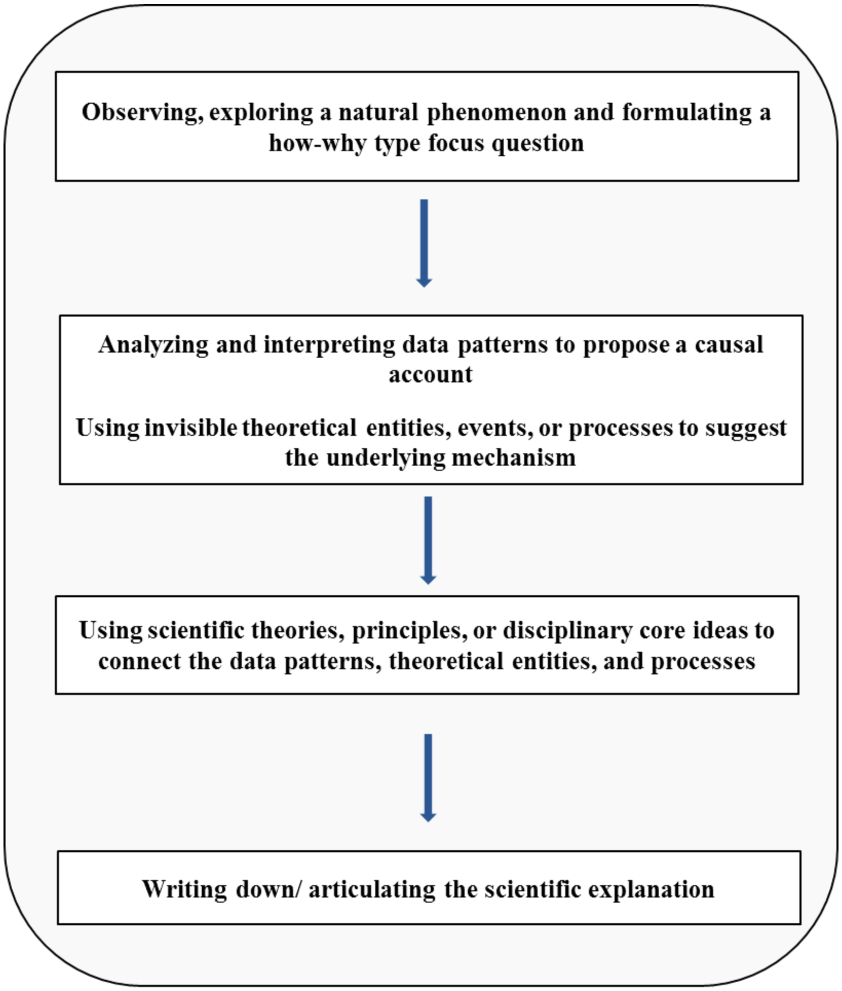

Figure 1. Explicating the process of constructing scientific explanations (Based on Authors 2017; Braaten & Windschitl 2011; Brigandt 2016; McNeill & Krajcik 2008; Sandoval & Milwood 2005)

Constructivist underpinnings of the proposed model

Piaget (1936, 1963) coined the terms *assimilation* and *accommodation* to describe how individual learners acquire new knowledge by either extending or refining their pre-existing cognitive schemas or knowledge structures about any given topic or domain. Here, the terms schemas or knowledge structures implies the ‘units of knowledge’ or ‘mental representations of facts and ideas about any given topic’ (Ausubel 1968; Authors 2017; Chi, Glaser, and Rees 1982; Novak 2002; Piaget 1963). He also coined the term *equilibrium* to describe the state of cognitive balance or minimal dissonance between learners existing knowledge structure and new experiences or knowledge encountered. Piaget emphasized that learners constantly strive to reach the state of equilibrium by either assimilating new information to extend or readjust their knowledge structures or accommodating new information to reconstruct the existing knowledge structures. Social constructivists extended Piaget's individual learning approach to include the social aspects of learning Vygotsky (1978) emphasized that learning is collaborative; in other words, the social negotiation of alternative beliefs, contradictions, or irregularities facilitates the assimilation and accommodation of new knowledge (Forbes and Davis 2010; Vygotsky 1978). Research on children's conceptions has shown that the alternative beliefs or explanations arise from their everyday experiences and are very resistant to change (Brown 1992; Driver and Easley 1978; Strike and Posner 1992). Conceptual change researchers have thus proposed the use of *cognitive conflict* as an instructional strategy to elicit students' ideas, which can then be negotiated to accommodate the scientifically accepted knowledge (Posner et al. 1982). To put it concisely, the constructivist tradition describes learning as a cognitively active, self-regulated, and collaborative as well as individual process of knowledge construction, embedded in an authentic task, question, or problem (Aebli 1983; Hugener et al. 2009).

Recent empirical studies have described three key features of constructivist, cognitively activating learning environments: *teaching of complex and interconnected subject matter*; *use of challenging tasks to orchestrate discussions*; and *initiate thoughtful-constructive discourse* (Förtsch et al 2016; Lipowsky et al. 2009; Authors 2016) These constructivist features have guided the design of several inquiry and argumentation oriented lesson-design models (e.g. Bybee et al. 2006; Chen and Steenhoek 2014). In this article, we demonstrate how the core practice of constructing scientific explanations can serve as a vehicle to plan student-centered, cognitively activating biology lessons. Authors (2017) described how German biology teachers engaged learners in constructing evidence-based explanations. Teacher first presented a context or real-life problem to engage learners in formulating explanation-oriented focus questions. Next, teacher used these questions to elicit students' pre-instructional ideas. Thereafter, students analyzed authentic data, interpreted data patterns, and developed causal-mechanistic explanations by connecting evidence with theoretical entities. This presented article builds upon these findings and proposes a six-phase model for planning explanation-oriented lessons.

Context

The study was conducted in an upper secondary biology classroom in a city-college in Munich, Germany. The grade 11 biology teacher was the primary participant. The biology teacher, who participated in this study, had attended a three-day course on integrating scientific inquiry, explanation construction, and argumentation in biology lessons. This course was designed and offered for the first time at our teacher training institute in the winter semester – 2016. This ensured that the biology teacher participating in this lesson planning and implementation study had already acquired a basic understanding of core scientific practices oriented biology teaching approaches. Grade 11 students, who participated in this study, articulated pre- and post-instructional explanations during the lesson (i.e. phase two and phase five).

The Six Phases of the Explanation-oriented Lesson-design Model

This study aimed to describe an explanation oriented lesson-design and demonstrate how it could be operationalized to plan and implement biology lessons. In this section, we describe the six phases of the model and demonstrate how they were operationalized to plan and implement a grade 11 lesson on the topic 'DNA and protein synthesis'.

Phase One: Presenting a hooking activity

A good introductory activity hooks a learner by showcasing the relevance of the topic and highlighting the disequilibrium between their existing knowledge and the new information or experience (Gagonon and Collay 2005; Piaget 1963; Posner et al. 1982). Teachers can, for example, use an experiment, activity, or visual to highlight an interesting phenomenon, contradiction, or regularity to generate students' interest in the topic being taught. Following-up a hooking activity with explanatory bridging questions can help elicit students' ideas, alternative conceptions, and pre-instructional explanations about the phenomenon under study.

In the lesson described here, the teacher showed a short video to generate students' interest in the genetic disorder 'sickle cell anemia'. Next, the teacher showed the microscopic image of red blood cells in a normal individual and in a patient suffering from the sickle cell anemia. Students' ideas were elicited using questions like: How is it that healthy human beings have round shaped red blood cells while sickle cell anemia patients have a mixture of round and sickle-shaped cells? What happens to the red blood cells in the sickle cell patients?

Table 1. Operationalizing the six phases of the explanation oriented lesson-design model

Lesson phase	Purpose of the phase	Activity used in the example lesson
Presenting a hooking activity	-to showcase the relevance of the topic -to highlight the cognitive disequilibrium	Teacher shows the video of a patient suffering from sickle cell anemia. Next, the teacher shows the microscopic image of the red blood cells of a normal individual and a patient suffering from sickle cell anemia. Teacher leads the discussion: How is it that healthy human beings have round shaped red blood cells while sickle cell anemia patients have a mixture of round and sickle-shaped cells? What happens to the red blood cells in the sickle cell patients?
Formulating a how-why type question	-to highlight the main content being taught in the lesson -to anchor the lesson on constructing scientific explanations	How are proteins such as hemoglobin synthesized in our body? And how can disorders like sickle cell anemia occur in this process?
Constructing the initial causal story	- to elicit students' pre-instructional explanations of the how-why type focus question	A causal story template (see figure 2) was used to elicit students' initial ideas about the focus question formulated in the previous phase. Later, students shared their causal story with the class.
Using authentic data, scientific facts, principles, and disciplinary core ideas to revise-refine	-to encourage the use critical thinking skills and reasoning skills in formulating scientific explanations	Activity 1: Analogy between constructing a building and protein synthesis was used to introduce the process of transcription and translation Activity 2: Next, students were given a short DNA sequence from a normal individual and sickle cell anemia patient. Students use the genetic code chart to first transcript this DNA

the causal story		into RNA and then into protein. The final amino acid sequence from the two individuals was compared and discussed: 1) to understand how sickle cell hemoglobin is different from the normal hemoglobin, 2) how this slight change affects the shape of red blood cells. Activity 3: Students worked in groups and sequenced the cards indicating the process of transcription and translation.
Discussing-writing the refined causal story	-to summarize the main science content developed in the lesson	Students were again provided with the causal story template to rearticulate the scientific explanations for the focus question.
Applying the causal-mechanistic knowledge in a new context or problem scenario	-to refine-apply the new knowledge acquired in the new lesson	Students were asked to use their understanding of the process of transcription and translation to suggest therapy for patients suffering from genetic disorders like sickle cell anemia.

Phase Two: Formulating a how-why type focus question

Brigandt (2016) emphasized that concrete explanatory aims or in other words specific and explanation oriented focus questions are an important element of explanation driven science learning environments. 'Explanatory aims' or questions not only clarify the *explanandum* (i.e. the phenomenon being investigated) but also the intended *explanan* (i.e. explanatory account) in a given context. Authors (2017) also found that teachers' use of explanation oriented focus questions guided the teaching-learning activities on constructing causal-mechanistic explanations. Hence, we recommend teachers to formulate concrete and explanation oriented focus questions for their lessons.

The eleventh-grade biology teacher formulated following focus question for the lesson on protein synthesis in cells: How are proteins such as hemoglobin synthesized in our body? And how can disorders like sickle cell anemia occur in this process?

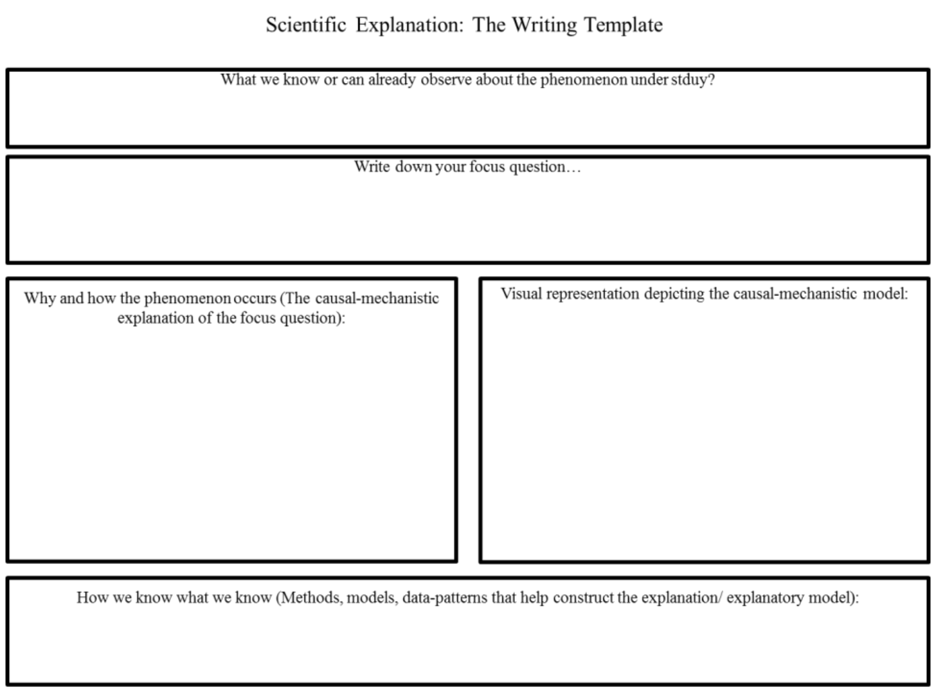

Figure 2. Scientific Explanation Writing Template

Phase Three:

Constructing the initial causal story

Both the constructivist and the conceptual change instructional approaches emphasize that classroom environments should encourage learners to present and discuss their pre-instructional ideas or preconceptions about the topic being taught. Eliciting learners' initial ideas helps recognize their pre-existing schemas or alternative conceptions about any given topic. Evoking

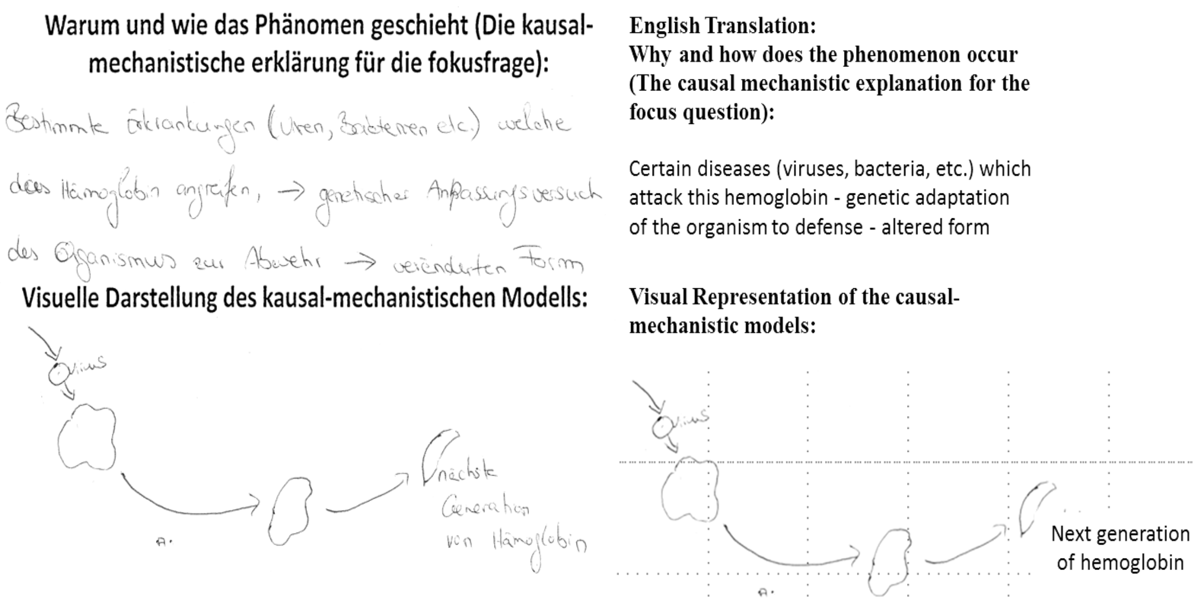

Figure 3. Pre-instructional explanation of a student - I

and discussing students' initial ideas can further highlight the cognitive dissonance and stimulate learners to assimilate or accommodate the new incoming information presented in the lesson (Authors 2017; Brigandt 2016; Gagonon and Collay 2005; Piaget 1963; Posner et al. 1982).

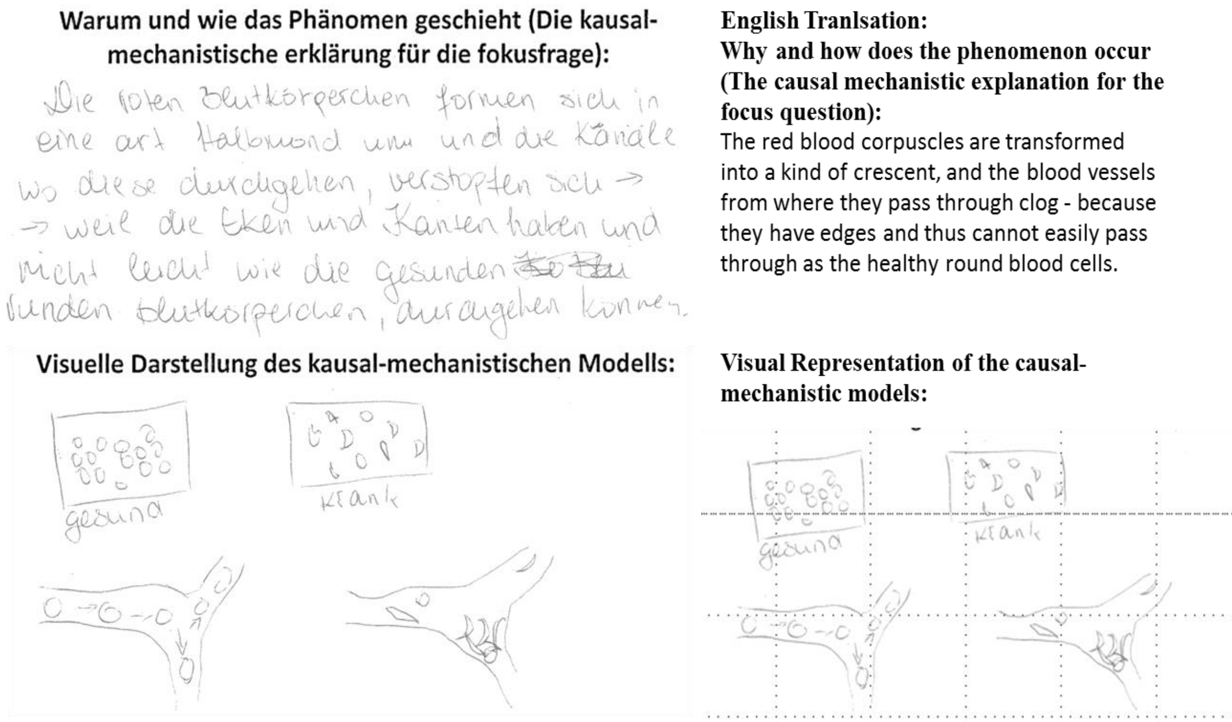

Figure 4. Pre-instructional explanation of a student - II

Moreover, the pre-instructional writing tasks help understand how the learners have perceived the information presented during the introductory phase and the way they relate this information to their prior knowledge (Wittrock 1992).

In the lesson on 'DNA and protein synthesis', we used a *causal story* template (see Figure 2) to elicit learners' initial ideas about the focus question formulated in the previous phase. Later, individual learners or groups shared their causal story with the class (see Figure 3 and 4).

Phase Four: Using authentic data, scientific facts, principles, and disciplinary core ideas to revise-refine the causal story

In the beginning of this phase, students could be engaged in 'thought experiments' or proposing and planning actual investigations or experiments that help validate or revise their causal stories presented in the previous phase (Authors 2017; Brigandt 2016; Bybee et al 2006; Chen and Steenhoek 2014;). Teachers can facilitate these discussions by asking probing questions that require students to not only suggest possible investigations but also describe how data or observations from this investigation can help validate their causal stories. Next, considering the time and resource constraints, students could be engaged in conducting actual investigations or knowledge construction activities that help make sense of the phenomenon under study.

In the lesson described here, students explored the process of protein synthesis by comparing it with the analogy of constructing a building. Next, students transcribed and translated a short sequence of DNA from a healthy individual and sickle-cell anemia patient. Afterward, students spotted the difference in the translated amino acid sequences and connected it with the altered shape of the hemoglobin in sickle cell anemia patients. The disciplinary core idea of structure and function was used to understand how sickle-shaped red blood cells can present difficulties to the patient. In the end, students worked in three groups to order and explore the key steps of transcription, RNA processing, and translation using the visuals and cue cards provided by the teacher.

Phase Five: Discussing-rewriting the refined causal story

In this lesson-design model, we demonstrate how the scientific explanation construction process can be used as a tool to drive learning. Encouraging learners to articulate the scientific explanations is an important part of this process. As students encountered new experiences through the phases described above, they formulated their own questions, analyzed and interpreted data patterns, and proposed the causal-mechanistic explanations by connecting data with the underlying theoretical entities and processes. It is thus important that students write down or articulate the scientific

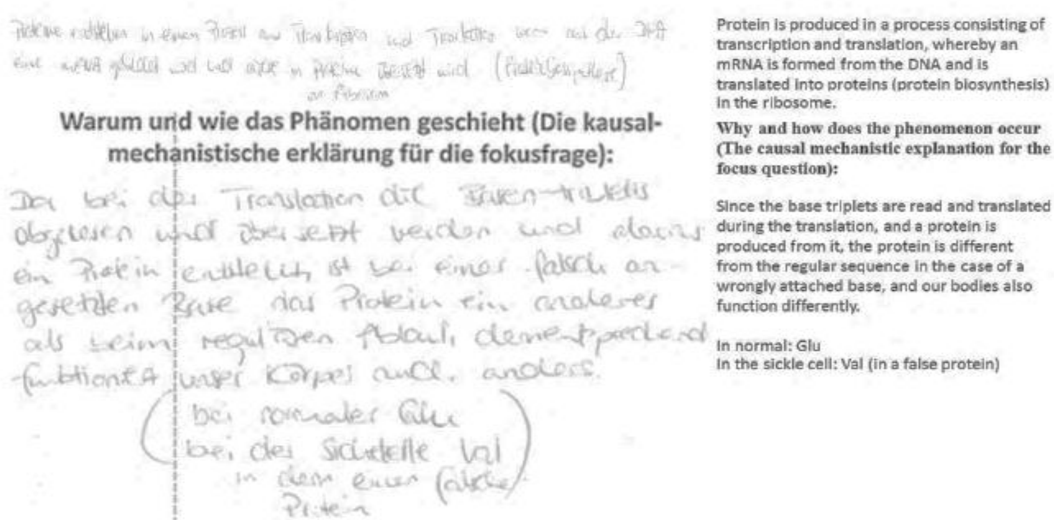

Figure 5. Post-instructional explanation of a student - I

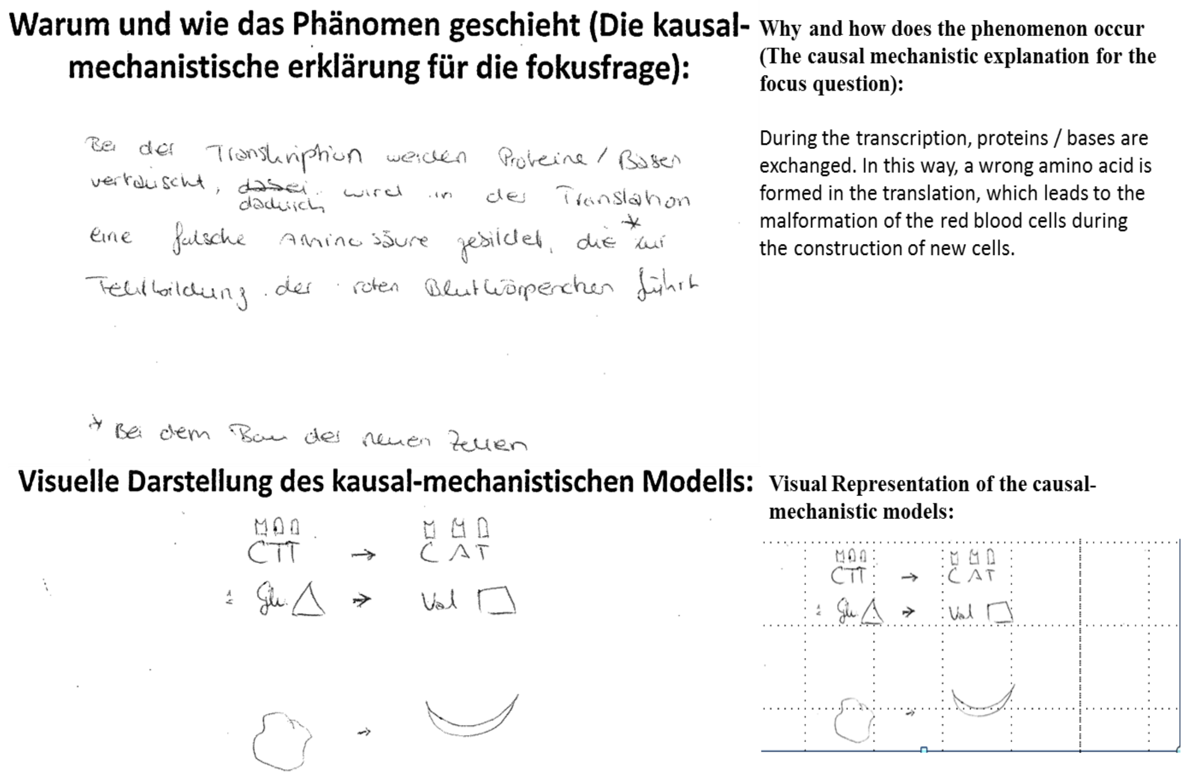

Figure 6. Post-instructional explanation of a student - II

explanations to showcase their understanding of the topic under study. Such elaboration tasks stimulate learners to reflect on their own understanding while connecting the facts, concepts, and ideas presented during the lesson (Wittrock 1992). In the lesson described here, students were asked to write down the refined scientific explanations in the causal story template (see Figure 2, 5 and 6). Rubric shown in Table 2 can be used to grade students' scientific explanations.

Phase Six: Applying the causal-mechanistic knowledge in a new context or problem scenario

Meaningful learning can be described as the acquisition of new knowledge or skills that can be retrieved and applied to new contexts or problem situations (Authors 2017; Mayer 2002). Thus, constructivist instructional designers recommend the use of application or extension tasks to monitor students' success in acquiring knowledge and skills pertaining to a given topic or domain (Gagnon and Collay 2005; Chen and Steenhoek 2014). Moreover, students' performance in the transfer tasks can inform teachers on their choice of content and learning activities used during the lesson. In the biology lesson described here, students were required to transfer their understanding of genes as specific DNA sequences and protein synthesis to propose a treatment for the genetic disorder – sickle cell anemia.

Table 2. Rubrics to evaluate the adequacy of students' scientific explanations

(Based on Braaten and Windschitl 2011; Brigandt 2016)

Basic	Intermediate	Advanced
- Learner explains a phenomenon using their prior knowledge of facts and commonly observed patterns	- Learner describes the phenomenon. - Learner mentions the patterns or trends in data and invisible underlying theoretical entities, events or processes that support the occurrence of a phenomenon.	- Learners describe the phenomenon. - Learner mentions the patterns or trends in data and invisible underlying theoretical entities, events or processes that support the occurrence of a phenomenon. - Learners connect data patterns with the underlying theoretical entities, events or processes using a unifying scientific principle, theory, or disciplinary core idea.

Conclusion and Implications

The presented article demonstrated how a student-centered, constructivist lesson-design model could support teachers integrate scientific explanation construction, an important scientific practice, into their regular biology lessons. The vignettes of teacher-student interactions from the phases one, two, and four depicted that the hooking activity and the formulating of focus question activated students to share their pre-instructional ideas and knowledge of facts about the topic (see Table 3). Students first presented ideas about how sickle-shaped red blood cells could obstruct blood circulation in our body. Next, students shared their about hemoglobin, a protein in red blood cells that helps transport oxygen. Thereafter, they presented their assumptions about what causes some individuals to produce sickle-shaped cells. At this point, teacher clearly formulated the focus question and asked students to write down their pre-instructional explanations. Again, this phase activated students' prior knowledge and highlighted their alternative conceptions about the topic, which were refined or replaced in the subsequent phases of the lesson. In the next phase, the students transcribed and translated a short DNA sequence of the healthy individual and that of the individual with sickle cell anemia with the help of the codon chart. This helped them identify that a wrong amino acid was inserted in the hemoglobin protein of the individuals suffering from sickle cell anemia. This evoked the core idea of structure and function, which helped students connect the data pattern with theoretical entities and develop an evidence-based causal explanation. Thereafter, students articulated and wrote down their explanations depicting the causal-mechanistic mechanism underlying the phenomenon. In conclusion, the vignettes corroborate our claim that the proposed lesson-design model cognitively activated learners and promoted a deeper understanding of the subject matter (Lipowsky 2009).

The analysis of lesson vignette also revealed some limitations of this model. Although the hooking activity successfully elicited students' prior knowledge, students found it difficult to clearly formulate the causal questions pertaining to the phenomenon. Future studies could investigate how the introductory dialogue could be organized to engage student participation in formulating scientifically oriented focus questions. More studies are also needed to understand how the use of first-hand versus second data or authentic text could influence the process of constructing evidence-based explanations (Delen & Krajcik, 2015).

Furthermore, two things were evident when comparing students pre- and post-instructional responses: 1) students came into the class with preconceptions or preliminary schemas, which are based on their everyday experiences and notions (Brown 1992; Driver and Easley 1978; Strike and Posner 1992). One student described sickle trait as a genetic adaptation to fight against certain viruses or bacteria that attack the hemoglobin (see Figure 1). Another student described the sickle cell trait (i.e. red blood cells transform into a crescent and clog the blood vessels) but did not explain its cause or mechanism (see Figure 2). On the other hand, students' post instructional explanations depicted how they employed their reasoning skills to connect their work on 'normal and sickle cell DNA strands' with their understanding of the 'mechanism of protein synthesis' to develop a causal-mechanistic explanation of the focus question: How are proteins such as hemoglobin synthesized in our body? And how can disorders like sickle cell anemia occur in this process (Brigandt 2016; Fischer et al. 2016; Teig and Scherer 2016; Zimmerman 2007)? One student described that the point mutation in the DNA sequence leads to the insertion of a wrong amino acid in the hemoglobin protein sequence. This, in turn, leads to the malformation of hemoglobin and thus the red blood cells. The mechanism was also depicted using a diagram to present the sequential chain of events leading to the sickle cell trait. Another student described the process of transcription and translation. In the next step, the student related their understanding of this process with their work on the normal and sickle cell DNA strands and pointed out that a false protein was formed, which could have caused the deformation of hemoglobin and thus the red blood cells in sickle cell anemia patients.

It is important to note here that this was students first attempt to develop authentic data based causal explanations. Although students' explanations were not very elaborate, we could see first evidence of how the model facilitated learners to work with data and develop evidence-based explanations. Future research in this regard could focus on how a teacher could provide rubrics and meta-cognitive clues that could scaffold students in constructing and articulating elaborate explanations of the focus question. One way to scaffold learners could be that they evaluate their pre- and post- instructional responses based on the rubrics described in Table 2. Students could also give each other feedback on how they could further refine their post instructional explanations that provide an elaborate account of what data was analyzed and how data patterns were connected with theoretical entities, both facts and core ideas, to present the causal chain of events underlying the phenomenon. In conclusion, we recommend more biology teachers to make use of this model as a lesson-design framework to integrate the authentic scientific practice of constructing scientific explanations in their regular lessons.

Acknowledgements

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Supplementary Material

Table 3. Vignettes of teacher-student interactions, highlighting their engagement in the knowledge construction process

Vignettes of teacher-student interaction (Phases 1, 2)	Student engagement in the knowledge construction process
L: The topic we are working on today is sickle cell anemia. Has anyone ever heard of this disease? *S1: The red blood cells are not round, but form such crescents.* *L: This is the carry. The symptoms she shows in this disease is the pain attack. How would that be expressed if a tissue gets too little oxygen?* *S: It turns blue or looks necrotic or* *L: For example. As you said, the cells look different in sickle cell anemia. Around healthy people, and here you see this deformation. That's why the name. Now please describe what you can see here so that the structure is described in its function or not by the shape that the blood cells have. What can you recognize?* *S: The rounds in the oval have a run through the blood - I do not know. And with the others it jams so it looks like there's a blood vessel sticking to it.* *L: Yes, traffic jam. Why is that? How is this traffic jam created?* *S: ... If these crescents have corners, so to speak, and can get stuck somewhere and get caught up with others* *L: Well, I do not know. I think I have not had a jam with such cells in my body. So I do not have this disease.* *S: That's genetic, hormones* *L: Guess - is nothing wrong. Just say what you think the reason is.* *S: I also think genetically. We talked about that last hour, that in some countries it is good that there are several because they adapt there. Um, for some diseases, the sickle cells are not vulnerable.* *L: What do you think about a disease spontaneously? Ok, genetically. Here we are and now agree. What are red blood cells actually for? Do you happen to know that?* *S: They transport oxygen* *L: Mhm, that's right. What do you call them?*	- Students compared the red blood cells of normal individuals and sickle cell patient and discussed how sickle cells could cause problems in the body. -Students shared their prior knowledge that red blood cells mostly contain hemoglobin, which is a protein. - Teacher-student interaction highlighted the cognitive dissonance: How are sickle shaped cells produced in some individuals? -Students presented their pre-instructional beliefs: 1) hormones 2) that it is a genetic disease, which is a kind of an adaptation in some countries.

S: Are these blood cells, is that it? hemoglobin *L: hemoglobin. What is hemoglobin if we continue this way?* *S: (…. Inaudible)* *L: And still further? Even more general?* *S: A protein* *L: Mhm, so what questions do we have to ask ourselves now? Which questions come to mind now? If we've already found out that this is apparently genetic, and that the red blood cell is a protein. Who is going to read aloud?*	
S: How are proteins synthesized in our body and how can genetic diseases such as sickle cell anemia occur during this process? *L: Is the question now clear during our discussion, why is this now? Yes? No? Maybe? Check.* *S: Yes*	In the next phase (i.e. phase 3) students write down the pre-instructional explanations of the focus question.

Vignettes of teacher-student interaction (Phase 4)	Student engagement in the knowledge construction process
L: Here we have a DNA strand from a normal blood cell, that is from a round, healthy one. And we have a strand of DNA from a sickle cell, a sick blood cell. It does not make you so complicated. Just write the letters. *………………….* *L: Have now translated the DNA into the mRNA - What comes next?* *S: The tRNA* *L: What does she do?* *S: The only transports, or what?* *L: Exactly, but what does it help to build?* *S: The proteins? Genes?* *L: Yes, but first she transports? What are the proteins made of?* *S: amino acid* *L: And now comes your gene sun, because now you have what you have generated. These base triplets are called the translate* *S: amino acid* *L: In amino acids.* *S: GAA is ....* *L: Exactly, you look in the middle of the G* *S: Glu ...*	- Students used the codon chart to transcribe and translate DNA strands of a healthy individual and a sickle cell anemia patient. - Next, they compared the RNA sequence and the amino acid sequence and identified the fault in the protein. - Teacher explained this as an example of point mutation.
L: I do not know it by heart, I have to confess. And then you write those shortcuts under each base triplet, okay? The code sun is read from inside to outside. Do you have enough books?..................... *L: Ok, that suits. I think that you could now come on slowly, how you could now answer your focus question from the beginning a bit more detailed.*	In the next phase (i.e. phase 4) students articulated the causal-mechanistic explanations of the phenomenon

L: Hmm, now let's take a closer look. Check if you have it like that. And then (student X) can tell a little bit more. *S: Yes, I think the mRNA has a different base .... So, a wrong reading and therefore completely different proteins*	highlighted in the focus question.

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4. Discussion

Findings obtained from the three studies, described in the previous chapter, are summarized and discussed in this chapter. Given that the previous chapter includes an elaborate discussion of results reported in these studies, this chapter goes one step further by describing how these results contribute to the overall aims of this dissertation and the current discussions in the field of science education research.

In the first section of this chapter, the descriptive, correlational, and qualitative obtained from the three studies were re-stated and reviewed in light of the literature. Next, the studies' limitations were discussed, and the directions for future research were outlined. Thereafter, the connections between the three studies were drawn, in order to suggest the practical applications of this doctoral work for educational practice and policymaking.

4.1. Summary of the Empirical Findings

This doctoral study focused on two key objectives. First, the German biology classrooms were analyzed for two of the three key aspects of cognitively activating instruction: teachers' use of challenging tasks and teachers' use of thoughtful-constructive discourse practices. Teaching features pertaining to these aspects were described and correlated with the student outcome variable: students' cognitive knowledge structure. Second, a lesson-design framework was developed to demonstrate how key aspects of cognitively activating instruction could be integrated into the everyday lessons. The descriptive-correlational segment showed a small magnitude positive effect of teachers' use of high-level cognitive processing on students' cognitive knowledge structure, measured using the concept mapping exercise. However, there was no significant effect of teachers' use of higher content complexity tasks on students' cognitive knowledge structure. Next, this analysis indicated that teachers' use of specific and challenging focus questions positively correlated with the outcome variable: students' cognitive knowledge structure, while the teachers' use of non-specific or simple focus questions did not predict students' cognitive knowledge structure. Finally, the planning and implementation of the eleventh grade lesson on 'DNA and protein synthesis' demonstrated how the explanation oriented lesson design model could be used to integrate the three aspects of cognitively activating instruction into the regular lessons (see Figure 3).

Theoretically devised coding protocols were used to analyze the teaching features pertaining to two of the three aspects of cognitively activating instruction. Challenging tasks were analyzed based on the two tasks characteristics: required level of cognitive processing, the complexity of task content. Blooms taxonomy of cognitive objective levels was adapted to analyze the cognitive processing level of tasks (based on Anderson & Krathwohl, 2001; Blooms, 1972; Blooms Taxonomy, n.d.; Craik & Lockhart, 1972; Ergönenc et al., 2014; Fischer et al., 2014; Krathwohl, 2002). The complexity of task content was analyzed using a three-level coding scheme: facts, connections, and concepts (based on Fischer et al., 2007; Neumann et al., 2008; Wadouh et al., 2014). Cohen's kappa for the coding protocol showed a good inter-observer agreement (Landis & Koch, 1977; Wirtz & Caspar, 2002). Likewise, teachers use of focus questions was analyzed using a rating system (based on Forbes & Davis, 2011; Schwille et al., 2011). The rating protocol showed a satisfactory percentage agreement (Wirtz & Caspar, 2002).

Cognitively activating instructional features were related to students' cognitive knowledge structure. For evaluating students' cognitive knowledge structure, we used the four concept map variables that were quantitatively coded in a previous study: the number of terms used, the number of relations drawn, the number of correct relations drawn, and the number of relations with deeper explanations for the relations drawn (Wadouh 2007; Wadouh et al., 2014). We used a factor reduction approach to identify latent variables that represent this theoretical construct. Principle component analysis indicated no sub-scales and thus the student scores on the above-mentioned four concept map variables were added together to form one factor: students' cognitive knowledge structure.

Last, the collaborative action research approach was used to design and implement lessons in a grade 11 classroom. Students pre- and post-instructional explanations were recorded using the scientific explanation construction templates. Students pre-instructional responses revealed a variety of preconceptions pertaining to the phenomenon being investigated. In contrast, students' post-instructional responses reflected how they connected authentic data patterns with theoretical entities to develop causal explanations of the phenomenon (Forbes & Davis, 2010; Krajcik & Mamlok-Naaman, 2006).

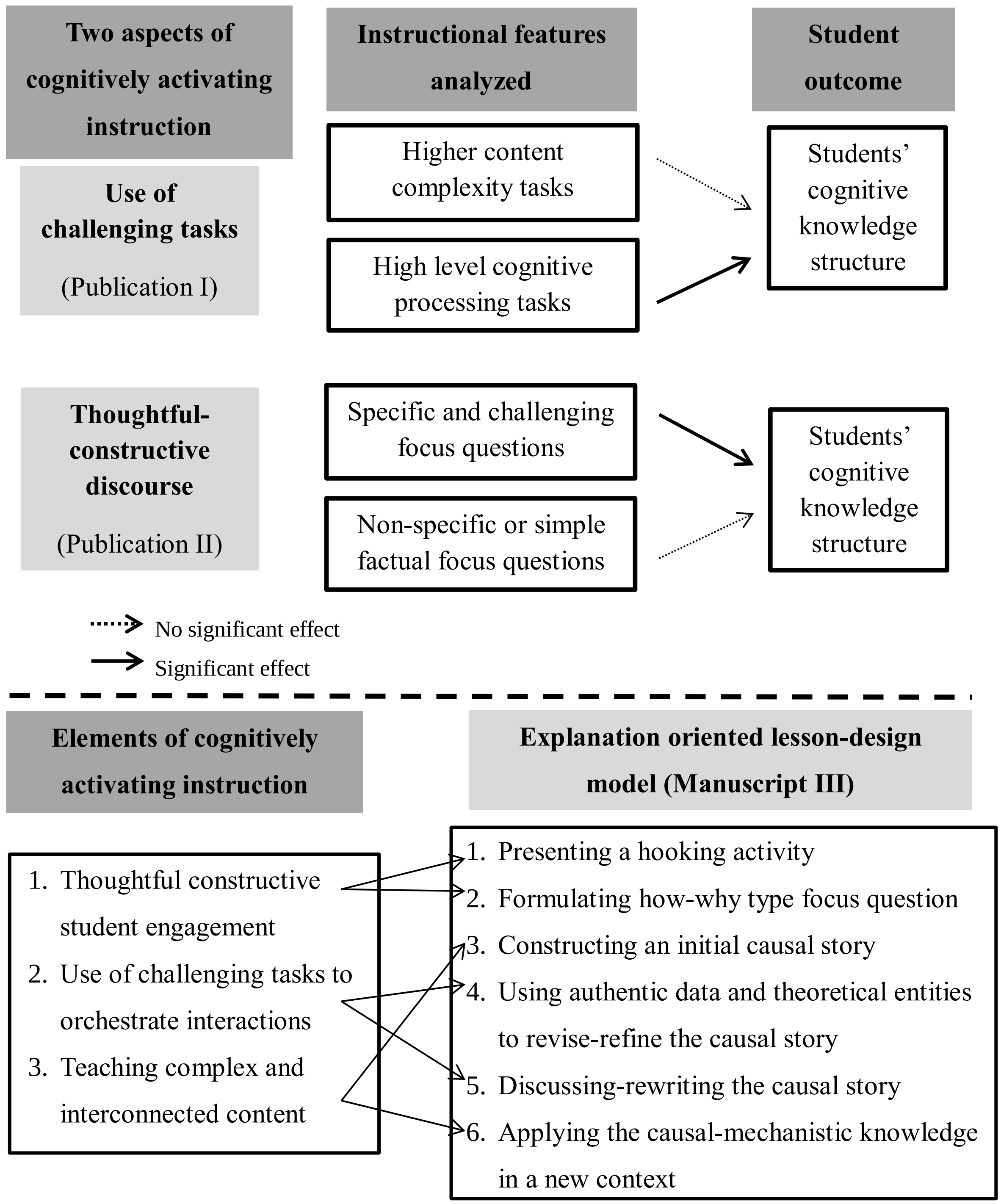

Figure 3.

Summary of the Empirical Findings. Effects of cognitively activating instructional features on students' cognitive knowledge structure. Translating key aspects of cognitively activating instructional approach into a lesson-design model.

4.1.1. Describing the Two Aspects of Cognitively Activating Instruction

The first objective of this dissertation was to describe the teaching features pertaining to two of the three dimensions of cognitively activating instruction: teachers' use of challenging tasks or learning opportunities, and teachers' use of thoughtful-constructive discourse practices.

Andersons' (1983) and Blooms' (1968) taxonomy of cognitive objective levels were operationalized to analyze teachers' use of high and low-level cognitive processing tasks in biology lessons. Likewise, a three-level coding scheme (i.e. factual recall tasks, connections level tasks, conceptual level tasks) based on Neumann et al (2008), Schönborn and Bögeholz, (2009), and Wadouh (2007) was used to examine the level of content complexity of new teacher initiated tasks. Analysis of tasks used in a pre-selected subsample of 38 out of 47 German biology lessons showed that only one-fifth of the tasks were set up at a higher cognitive level and thus teachers mostly posed low-level cognitive processing tasks. Similarly, only one-third of the tasks were at a higher content complexity level, and very few of these tasks were at the highest level of conceptual content complexity. Our findings are consistent with the results reported in the earlier doctoral work, which analyzed this same sample of videotaped lessons. Jatzwauk (2007) and Jatzwauk, Rumann, and Sandmann (2008) observed 45 out of 47 lessons to analyze the written tasks that were used during the student work phase. This means teacher initiated oral tasks used during the whole class discussions were not analyzed in this study. A total of 273 tasks, on an average six tasks per lesson, were identified and analyzed in this study. These tasks were analyzed for the following categories of cognitive processing: sensory-motor (non-cognitive activities), recording of information, recording and presentation of information without changing the form of presentation, reproduction from memory, convergent thinking, and divergent thinking. Jatzwauk et al (2008) found that two-third of the tasks used in biology lessons were at a lower level of cognitive processing. These findings are consistent with the results obtained in the previous studies, which have reported that German teachers mostly ask short-answer tasks that demanded low-level cognitive processing of the content taught in the lessons (Hiebert, 2003; Jordan et al., 2008; Seidel, 2005, 2007). Similar findings were reported in a recent study that analyzed teacher initiated tasks in a sample of 28 grade 6 lessons (Förtsch et al., 2017). This study analyzed the cognitive level of tasks based on the following categories: reproduction and selection (low level), organization and integration (high level). Similarly, the content complexity of tasks was analyzed based on the three categories: facts, relations, and concepts. This study also found that two-third of the tasks observed in the biology lessons were at lower level of cognitive processing. Additionally, the study reported that teachers rarely set up concept level tasks, while teaching the biology topics. These findings again corroborate our claim that biology teaching culture in Germany predominantly focuses on transmitting factual information with the help of low-level cognitive processing tasks and lower content complexity tasks.

The second article employed a rating approach to examine teachers' use of focus questions in the videotaped biology lessons. Lessons were rated based on the following theoretically devised categories: no use of focus questions, teachers' use of specific and challenging focus questions, teachers' use of simple factual level focus questions, and teachers' use of non-specific focus questions (Forbes & Davis, 2010; Nawani et al., 2017). Descriptive analyses of our sample depicted that very few teachers used the focus questions to initiate or anchor content-related discussions. Furthermore, fewer teachers used explanation-oriented specific and challenging focus questions to engage learners in co-constructing explanations of phenomena or life processes. These results describe for the first time how focus questions were used in the naturalistic biology classroom settings to initiate and direct content-related discussions. However, these results, in a way, are broadly consistent with the findings reported in the previous studies, which stressed that German teachers mostly used a teacher-centered question-developing approach to develop factual level content related to a topic under study (Hiebert et al., 2003; Hugener et al., 2009). These findings are of direct practical relevance, in order to design and implement reform science lessons. Science education reforms have stressed that students should be engaged in answering testable or in other words scientifically oriented questions (National Research Council (NRC), 2012). Teacher education programs can benefit from these findings by tailoring their professional development initiatives to specifically help teachers formulate and integrate focus questions in their regular lessons (Forbes & Davis, 2010; Nawani et al., 2017). In sum, these findings provide a base to help teachers reflect on their own teaching practices and to explore how novel practices such as use of specific and challenging focus questions could direct the lessons on constructing conceptual knowledge about the topic under study.

4.1.2. Correlations Between Aspects of Cognitively Activating Instruction and Students' Knowledge Structure

The second objective of this doctoral study was to ascertain the influence of cognitively activating teaching features on students' cognitive knowledge structure. In this section, we discuss the correlational findings.

First, the multilevel modeling showed a small magnitude positive effect of teachers' use of high-level cognitive processing tasks on students' cognitive knowledge structure. Here, the students' prior knowledge and students' interest in biology-related activities were used as covariates in the final models. These findings are in line with the previous findings that have shown the positive effects of high-level cognitive processing tasks on students learning (Stein and Lane, 1996; Stein et al., 1996; Hiebert et al., 2003). Moreover, the recent study by Förtsch et al (2017) substantiates our findings that teachers' use of high-level cognitive processing tasks has a positive impact on students' conceptual knowledge. However, given that our findings are based on a limited sample and the results consist of correlational analysis, the causal relations must be interpreted with utmost caution. Moreover, Jatzwauk (2008) in their study found that increased use of challenging tasks in classes with little to no prior knowledge is associated with lower learning gains. They also stressed that students with little prior knowledge can learn more successfully if they have a lot of time to work on a smaller number of tasks. These findings have important implications when coupled with the findings obtained from our study. Teachers in Germany mostly use the question-developing teaching approach to transmit important biology knowledge. Students with little prior knowledge could feel overwhelmed by too many tasks and thus may not efficiently integrate new information into their existing knowledge structures. It is thus essential that teachers set up fewer cognitively activating tasks and support learners in utilizing higher order thinking processes in order to answer these tasks.

Second, the correlational analysis focused on ascertaining the impact of teachers' use of higher context complexity tasks on student learning. Contrary to expectations, we did not find any correlation between teachers use of higher content complexity tasks and students' cognitive knowledge. One reason for such unexpected findings could be that teachers mostly set up factual level tasks in our sample of videotaped biology lessons. Although there were a few connection level tasks, teachers rarely used concept level tasks in the lessons. Another reason could be lack of teachers' pedagogical content knowledge to handle higher content complexity tasks. The previous naturalistic studies on German mathematics and biology classrooms have shown that teachers mostly used short-answer questions to invite student participation (Hiebert et al., 2003 Jordan et al., 2008; Kunter et al., 2005). In such a scenario, it could be assumed that teachers either did not receive adequate training to formulate or set up cognitively activating tasks in their regular lessons. In sum, these findings suggested that teachers could benefit from the professional development opportunities that enhance their skills to formulate and implement challenging tasks.

Furthermore, the results obtained from this doctoral study demonstrated for the first time how teachers' use of focus questions influenced students' cognitive knowledge structure. The teachers' use of specific and challenging focus questions positively predicted students' cognitive knowledge structure. In contrast, there was no effect of teachers' use of non-specific or simple focus questions on students' cognitive knowledge structure. One reason for such findings could be that specific and challenging focus questions directed the lesson activities on co-constructing scientific explanations of key phenomena or life processes. These questions required students to analyze authentic data, interpret authentic text or information, and build connections between the data pattern and relevant theoretical entities such as scientific terms, facts, principles, or disciplinary core ideas to formulate causal explanations (Braaten & Windschitl, 2011; Brigandt, 2016; Sandoval & Reiser, 2004). Conversely, non-specific focus questions did not highlight the most important content being taught in the lessons. Similarly, the simple factual questions required the recall or paraphrasing of canonical factual knowledge to arrive at a scientifically appropriate answer. Consequently, these questions directed the lessons on highlighting, recalling, and reviewing factual level information about the topic under study (Forbes & Davis, 2010; Nawani et al., 2017). In sum, teaching that emphasized the transmission of isolated facts was less beneficial in enhancing students' cognitive knowledge structure, which essentially represent the interconnectedness of their knowledge about any given topic (Wadouh et al., 2014; Nawani et al., 2016; Nawani et al., 2017). Again, given that our findings are based on a limited sample and the results consist of correlational analysis, the causal relations must be interpreted with utmost caution.

4.1.3. Comparing the Classroom Teaching-Learning Processes

The classroom teaching-learning process in two lessons where teachers used specific and challenging focus questions was compared with the process in the other two lessons, where teachers used non-specific or simple focus questions. This comparative case analysis revealed that on one hand teachers used real-life scenarios or problems as a starting point to formulate explanation-oriented specific and challenging focus questions. Thereafter, teachers used authentic data or text interpretation activities to engage learners in constructing causal-mechanistic explanations of the focus questions. In sum, teachers use of specific and challenging focus questions required learners to build interconnections between data patterns and theoretical entities and thus assimilate (or accommodate) this interconnected knowledge in their existing knowledge structures. These findings again corroborate our claim that the specific and challenging focus questions helped enhance students' topic-related knowledge structure (Anderson & Krathwol, 2001; Ausubel, 1968; Forbes & Davis, 2010; Krajcik & Mamlok-Naaman, 2006; Mayer, 2002).

Conversely, teachers used recall and paraphrase questions to formulate description-oriented, simple factual level focus questions. Furthermore, the teaching-learning activities focused on presenting, highlighting, and reviewing the factual level information required to answer the focus questions (Nawani et al., 2017). These findings concur with the propositions in the theoretical literature, which emphasize that explanatory aims, in this case the specific and challenging focus questions, anchor the classroom discussions on co-constructing explanations; on the other hand, descriptive aims or description oriented focus questions anchor the classroom interactions on acquiring the canonical knowledge of facts, terms, and definitions (Forbes & Davis, 2010; Krajcik & Mamlok-Naaman, 2006). Moreover, the findings corroborate our claim that teachers' use of factual level focus questions does not stimulate construction of interconnected knowledge and thus might not be very effective in helping learners extend or refine their knowledge structures (Mayer, 2002).

4.1.4. Integrating Aspects of Cognitively Activating Instruction into the Biology Lessons: An Explanation Oriented Lesson-design Model

The third aim of this study was to propose a lesson-design model that supports teachers in planning and implementing cognitively activating biology lessons (Lipowsky, 2009). In this doctoral work, we demonstrated how the proposed six-step explanation oriented lesson design model helped teachers plan and implement a grade 11 lesson on the topic 'DNA and protein. The microphone was used to audiotape the lesson discourse. Additionally, students were asked to write down and visually represent the pre- and post-instructional causal explanations of the phenomenon.

We first analyzed the audiotaped discourse to understand how different phases of the lessons facilitated student engagement in the knowledge construction process. Analysis of vignettes of teacher-student interactions revealed that the hooking activity phase and the formulation of focus question phase successfully activated students' prior knowledge and helped elicit their preconceptions about the topic under study. Furthermore, the vignettes from the fourth phase showed that how students were engaged in analyzing data, interpreting data patterns, and connecting them with theoretical entities such as facts, principles, and core ideas to develop coherent explanations of the phenomenon. However, although the analysis of vignettes provides initial evidence of the success of the proposed model in facilitating knowledge construction, it remains to be investigated further how students could be involved in formulating explanatory aims or focus questions at the beginning of the lessons. It also remains unclear how teachers use of thought experiments and second-hand data versus the first-hand data collection affect the way students develop evidence-based explanations. Delen and Krajcik (2015) stress that students constructed stronger explanations when analyzing the first-hand data as compared to when they used the second-hand data to develop explanations.

In the next step, students' pre- and post-instructional responses of focus questions were analyzed. The comparative analysis revealed two important findings: First, students came into the classrooms with preconceptions or pre-existing knowledge structures as evident in their pre-instructional responses (Driver & Easley, 1978; Strike & Posner, 1992). Second, students were able to generate data patterns and connect them with theoretical entities to formulate causal explanations (Brigandt, 2016; Teig & Scherer, 2016; Zimmermann, 2007). However, these explanations did not completely depict the causal chain of events underlying the phenomenon of sickle shaped red blood cells instead of red blood cells observed in some people. It is however important to note that this model grade 11 lesson was students first encounter in explanation oriented biology learning. Thus, it can be assumed that repeated experiences could help students internalize this knowledge construction process. Another way could be to further scaffold students in articulating causal explanations. Students could be provided with rubrics that clearly describe the key components of coherent and elaborate causal explanations. Clear and concise rubrics could help students review or refine their explanations and also provide peer feedback on how these explanations could be further refined.

4.2. Limitations

The limitations pertaining to the re-analyzed sample, design of the study, and generalizability of findings obtained are discussed in this section. First, the sample size and data collection are the most important limitations of this doctoral work. As students' concept mapping related data was not available for all the 47-videotaped lessons, only 30 lessons were analyzed in the empirical studies described in the previous chapters. Additionally, the videotaped lessons included only one lesson per teacher, which raises concerns with regard to the stability and consistency of teaching patterns observed.

Second, although the pre-post naturalistic study design enabled the analysis of cognitively activating teaching features employed in the typical German biology lessons; additional teacher and school level factors could have influenced the outcome variable analyzed in this study. Moreover, the observational nature of the study did not allow the manipulation of the cognitively activating teaching features, and thus could have led to the low magnitude of correlations reported in the articles. Third, even though the analysis of real-life videos and high objectivity obtained in the coding process reflect the validity and reliability of findings reported; several factors pose limitations concerning the generalizability of this doctoral work. Data re-analyzed in this dissertation was collected from a set of pre-selected schools and teachers, who voluntarily agreed to take part in the teaching effectiveness study. In brief, the data were not selected randomly and thus results obtained must be carefully interpreted. Furthermore, although the teachers were not given any information regarding key aims or objectives of the study, it is still arguable whether the videotaped lessons represent the typical features that German biology teachers used in their regular practice. It must also be debated how the presence of an external observer or the video camera in the classrooms could have affected the teacher as well as students’ behavior. The previous studies in this regard, however, have asserted that teachers’ instructional behavior more or less remains stable in the absence of a long-term training intervention or specific request by the observer videotaping the lessons (Praetorius, Pauli, Reusser, Rakoczy, & Klieme, 2014)

Fourth, most of the lessons analyzed in this doctoral dissertation were collected from the Gymnasium track secondary schools of the North-Rhine Westphalia state in Germany; thus, it cannot be claimed that similar teaching practice or correlations could be obtained, while analyzing lessons collected from other school tracks such as *Realschule* or *Hauptschule* (Baumert et al., 2004). Moreover, in order to correlate teaching features with student level variables, lessons pertaining to one particular theme 'blood and circulatory system' and the pre-post assessments pertaining to the same topic were collected from the grade 9 biology classrooms; hence, these results cannot be generalized to primary grade biology classrooms. We thus strongly recommend that these observational studies should be replicated for various age groups, contexts, and school tracks to determine their effectiveness in supporting student learning.

Another limitation pertains to the outcome variable: students' topic-related knowledge structure. During the literature review, we found that concept mapping is indeed one of the promising tools to evaluate the interconnectedness of students' knowledge about a certain topic (Neumann et al., 2008; Sumfleth et al., 2006). However, it is essential to critically reflect upon the problems or difficulties that students might have faced while completing this task, particularly in the absence of any prior experiences or training in constructing concept maps. This could have been one reason why we obtained a very small intra-class covariance, even though noticeable variations were observed in teachers' instructional styles. Future studies could thus collect students' view on the concept mapping tasks and can train them on the process of constructing concept maps. Future studies could also include additional tasks that require students to construct causal-mechanistic explanations or apply their understanding of concepts in a given scenario (Scheerens, Luyten, Steen, & Luyten-de Thouars, 2007).

Lastly, in this doctoral work, we only observed teacher actions or utterances, in order to analyze the cognitively activating instructional features. However, students' actions are an important aspect of the cognitive activation construct. Analysis of student actions or responses, for example, students' answers to teacher initiated challenging tasks could have helped understand how these dimensions of cognitively activating instruction influenced the classroom-teaching learning process.

4.3. Further Research

This doctoral work followed a specific trajectory: First, two of the three dimensions of the cognitively activating instruction construct were operationalized, in order to describe the German biology lessons. Next, these teaching features were correlated with students' topic-related knowledge structure. Last, we developed an explanation-oriented lesson design model for planning cognitively activating biology lessons (see Figure 3). These findings are relevant to further enhance the science teaching practice in Gymansium secondary and upper secondary classrooms. Baumert et al (2004) found that teachers and students experience of cognitive activation varies significantly and is dependent on the grade level and also the school track. To further elaborate, the study found that students from *Hauptschule*, the lowest-level school tracks in Germany, reported a higher value of cognitive activation than their counterparts from the school tracks *Realschule* and *Gymansium*. Hence, it cannot be assumed that integrating cognitively activating features in regular lessons will facilitate learning for students of lower grades as well as students from the school tracks *Hauptschule* and *Realschule.* One recent study found a positive effect of teachers use of higher order cognitive processing tasks in grade 6 classrooms on students' performance in a knowledge test (Förtsch et al., 2017); similar correlational studies with regard to other cognitively activating instructional features such as teachers' use of complex and interconnected biology content and thoughtful discourse practices such as specific and challenging focus questions could throw more light on how these instructional features influence student learning for various age groups and academic school tracks. Future studies in this regard should examine how the individual aspects of cognitively activating instruction affect students' cognitive outcomes (e.g., application of knowledge test, constructing scientific explanations) and affective outcomes (e.g., situational interest in the classroom, engagement with the subject, interest in the subject and subject-related activities), which are essential to enhance their domain-specific competencies in biology (Baartman et al., 2007; Neumann, 2011).

Additionally, we strongly emphasize that future studies should carefully blend the elements of interventional and naturalistic study designs to ensure that the lesson videos capture novel science teaching approaches, which can then be investigated for their effectiveness in enhancing student learning. As an example, the interventions could support teachers in integrating interconnected biology content, challenging tasks, or focus questions into their lessons. In the next step, the teaching practice could be videotaped to examine 1) how teachers integrated these novel practices in their lessons, 2) how students were engaged in these novel practices, and 3) how these features influenced students cognitive as well as affective outcomes.

Recent empirical studies have found that teachers mostly use fact oriented low cognitive level teaching strategies to transmit biology content (Förtsch et al. 2016; Nawani et al., 2016, 2017; 2017; Roth et al., 2006). Teacher preparation programs must thus address this issue by helping teachers integrate concept oriented teaching practices in the biology lessons. Research on teacher professional development has demonstrated the effectiveness of video-based lesson analysis in supporting teachers reflect on their own teaching practice and integrate novel instructional ideas like coherent science storyline approach in their regular lessons (Roth et al., 2011). Similarly, Hanuscin et al. (2016) demonstrated how conceptual science storyline probes and collaborative lesson planning activities could help enhance teachers pedagogical design capacity to construct coherent conceptual storyline lessons. Future research studies could investigate how these professional development approaches could be used to enhance biology teachers pedagogical design capacity and their ability to implement cognitively activating teaching strategies in their regular lessons (Shulman, 1986; Magnusson, Krajcik, & Borko, 1999).

In this doctoral research, we collaborated with one grade 11 biology teacher to demonstrate how the core practice of constructing scientific explanations could be integrated into the biology lessons to plan and implement cognitively activating biology lessons. However, more research is needed to understand how the proposed explanation-oriented model could be used to plan lessons for primary grade levels. More research could also be devoted to understanding how first-hand versus second-hand data and teacher scaffolding during the explanation construction and explanation articulation phases could enhance students' skills to formulate coherent and evidence-based explanations. Additionally, new research could also focus on investigating how teachers could be supported in integrating scientific explanation oriented teaching practice into their biology lessons. There is evidence that lesson cycle based preparation programs enhance teachers pedagogical design capacity to plan and implement lessons based on specific instructional approaches (Maruta, 2011; Meyer & Wilkerson, 2011). A great deal of research could thus be devoted to developing similar teacher preparation programs, which support teachers in planning and implement biology lessons based on the explanation oriented lesson-design model.

4.4. Implications for Educational Practice and Policymaking

Future scientific jobs in the age of information and technology will demand knowledge workers to demonstrate domain-specific competencies, required to accomplish the non-routine jobs or tasks assigned in the workplace. Here, the term ‘competencies’ refers to ‘connected pieces of knowledge, skills, and attitudes that can be used to solve a problem’ (Baartman, Bastiaens, Kirschner, & van der Vleuten, 2007, p.5). Educational policy reforms have responded to such changing workplace scenarios by rewriting the national science and mathematics education standards, which emphasize that science and mathematics classrooms should support students acquire domain-specific competencies essential to succeed in future jobs, rather than transmitting unrelated domain-specific knowledge or skills (Baartman et al., 2007; Neumann, 2011). Educational research has thus focused on investigating the theoretical constructs and domain-specific teaching approaches that can help teachers meet these reform science-teaching goals. It is here that this doctoral research is situated.

Cognitive activation is an important domain-specific aspect of instructional quality. A substantial and growing evidence base has confirmed that cognitively activating instruction can positively influence students’ cognitive and affective outcomes (e.g., Lipowsky et al., 2009; Förstch et al., 2016; Nawani et al., 2016). Within this doctoral research, we developed a theory-based cognitively activating instruction model and empirically tested the teaching features pertaining to two of its three key dimensions: teachers’ use of challenging tasks and teachers’ use of focus questions to create thoughtful-constructive discourse. We also proposed a lesson-design model that demonstrates how the epistemic activities underlying scientific explanation construction can guide the planning of cognitively activating biology lessons (see Figure 4). Findings obtained from this doctoral work have implications for both educational practice as well as policymaking.

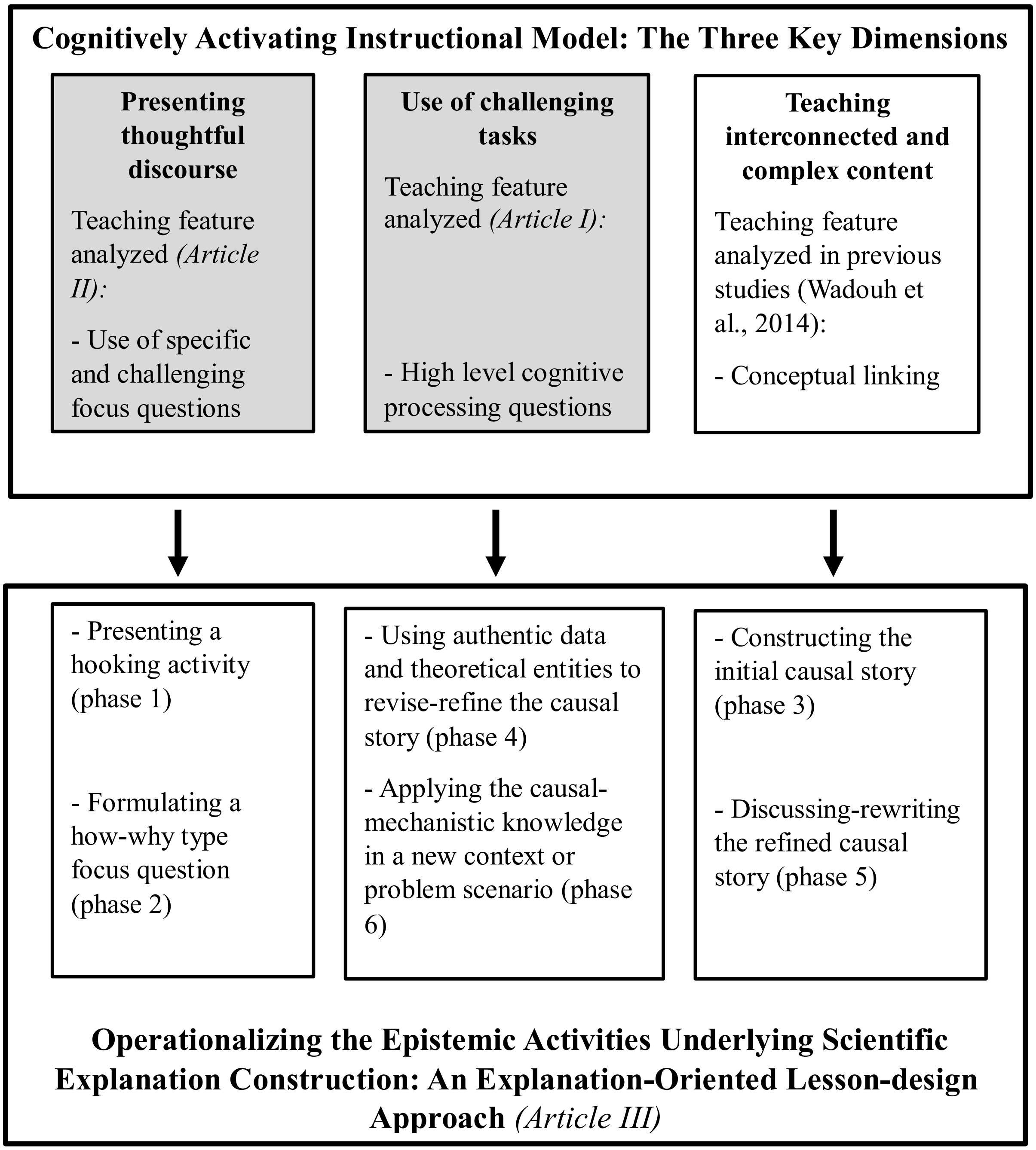

Figure 4.

A cognitively activating instructional model to move teaching away from transmitting facts to co-constructing scientific explanations

First, the descriptive findings obtained from this doctoral research depict that teachers mostly used low cognitive level and lower content complexity tasks to transmit the isolated knowledge of facts, terms, or meanings. One reason for such findings could be that teachers often find it difficult to integrate these novel instructional features into their regular lessons (Chen & Steenhoek, 2013, 2014). These findings particularly inform the teacher educators and practitioners about specific concerns that should be addressed during the teacher preparation and in-service teacher professional development programs. The findings also inform policymaking in the fields of teacher education and teacher recruitment. Policy reforms must ensure that in-service teachers and future teachers receive adequate training and material resources, required to integrate novel instructional approaches such as cognitively activating instruction into their everyday lessons. Moreover, the teacher recruitment policies must ensure that the teaching workforce entering classrooms has acquired adequate competencies needed to meet the science education goals.

Teacher education research has shown that teachers benefit from the professional development opportunities that enhance their professional vision, pedagogical design capacity, and ability to implement novel instructional strategies (Shulman, 1986; Magnusson, Krajcik, & Borko, 1999). Here, the term ‘professional vision’ implies teachers’ ability to notice specific features of instruction and explain their relevance and importance (Seidel, Blomberg, & Stürmer, 2010; Sherin, 2007); while, the terms ‘pedagogical design capacity’ and the ‘ability to implement novel instructional strategies’ refer to teachers’ abilities to plan and implement lessons based on a novel instructional approach. Theory-informed coding protocols developed for this doctoral work can be used to develop teachers’ professional vision for the following features of cognitively activating instruction: high-level cognitive processing tasks, higher content complexity tasks, and explanation-oriented specific and challenging focus questions.

More importantly, the empirically tested cognitively activating instructional model can be used as a guiding framework for teacher professional development programs. Recent studies demonstrated the effectiveness of video-based lesson observation and Japanese lesson cycle techniques in enhancing teachers pedagogical design capacity and their ability to implement novel instructional strategies (Roth et al., 2011; Hanuscin et al., 2016; Maruta, 2011; Meyer & Wilkerson, 2011). The cognitively activating instructional model and the coding protocols developed for this doctoral work can be used to develop similar teacher professional development programs.

Forbes and Davis (2010) emphasized that beginning teachers' need additional support in integrating such reform science teaching approaches into their everyday lessons. Theory-based constructs and coding instruments for teachers' use of focus questions and challenging tasks can direct the design of similar professional development programs. Similarly, the explanation-oriented lesson-design model and the exemplary biology lesson on the topic 'DNA and protein syntheses' could guide the planning and implementation of reform science lessons. The new science education standards require the meaningful integration of core science practices and disciplinary core ideas into the regular lessons. The proposed model demonstrated how epistemic activities underlying scientific explanation construction could promote the use of disciplinary ideas as conceptual tools to make sense of the phenomena under study. Professional development programs could specifically focus on helping teachers plan and implement lessons based on this model, which in turn can enhance their pedagogical design capacity and their ability to implement novel instructional strategies. In our university, we have already used this model to develop a teacher preparation program. In this program, the teachers first analyzed the transcripts of pre-selected biology lessons to notice and explain the six steps of the model. Next, teachers worked in groups to plan lessons based on this model. In the final step, plenary discussions were held to discuss and improve these lesson plans.

In conclusion, the cognitively activating instructional model, the coding protocols for two of its three dimensions, and the explanation-oriented lesson design model can serve as both guiding frameworks as well as the lesson-analysis tools for designing teacher professional development programs.

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6. Abbreviations

BMBF	German Federal Ministry of Education and Research
KMK	Standing conference of the Ministers of Education and Cultural Affairs of the Länder
PCK	pedagogical content knowledge
NES	National Education Standards
NGSS	Next Generation Science Standards
QuIP	Quality of Instruction in Physics
TIMSS	The Third International Mathematics and Science Study
Pythagoras	The Quality of Instruction and Mathematical Understanding in Different Cultures of Instruction
PISA	Programme for International Students Assessments

7. Curriculum Vitae

Personal Data

Name	**Jigna Srichand Nawani**

Education

2012 – Present	**Doctoral Student (Biology Education)** Ludwig-Maximilians University, Munich, Germany
2000 – 2002	**Master of Science (Environment Science)** Gujarat University, Ahmedabad, India Grade: First Class
1997 – 2000	**Bachelor of Science (Biochemistry and Chemistry)** Gujarat University, Ahmedabad, India Grade: First Class

Work Experience

2012 – Present	**Doctoral Researcher & Course Instructor** Ludwig-Maximilians University, Munich, Germany **Project Title:** Video-based Investigation of Teaching Effectiveness in German Biology Classrooms **Courses Developed/ Taught:** • Implementing video-based empirical studies to investigate teaching effectiveness and teacher professionalism (offered to the masters-doctoral students of learning sciences) • Integrating scientific inquiry, explanation construction, & argumentation in biology classrooms (offered to the pre-service biology teachers)
02/2010–10/2010	**Pedagogical Researcher** Redbricks Education Foundation, Ahmedabad, India • Organized curriculum design and teacher professional development programs for the early childhood section of the school • Worked with their design and training team to create mathematics and science literacy learning environments based on Montessori, Reggio-Emilia, and Theme-based teaching approaches
05/2008–10/2009	**Consultant - Curriculum and Pedagogy** Small Wonders School, Jaipur, India

- Used evidence-based developmentally appropriate milestones as a framework to develop early childhood learning environments and teacher professional development programs.
- Designed interest centers (multiple intelligences learning corners) for their preschool program

04/2007–04/2008 **Mathematics Curriculum Developer**
Riverside Education Foundation, Ahmedabad, India
- Designed and coordinated their mathematics literacy programme
- Developed math lab that catered to children ages 3 until 12 years

07/2006–03/2007 **Science Content Developer**
Educational Initiatives, Ahmedabad, India
- Worked with their large-scale assessment team to develop, translate, and implement the nation-wide science-mathematics assessment survey

12/2002–04/2006 **Science Educator**
Vikram A. Sarabhai Community Science Centre, Ahmedabad, India
- Conceptualized and implemented science outreach initiatives like science fairs, mobile science-math labs, rural science-math teacher training programs
- Developed project proposals and project reports for their outreach programs
- Co-ordinated content development and print production of children science publications and rural science-math teacher training manuals

Membership/ Affiliations

2012 – present **Member of the Doctoral Training Program (Munich Centre of the Learning Sciences)**
Ludwig-Maximilians University, Munich, Germany

2013 – present **Associate member of the International Doctoral School REASON (Elite Network of Bavaria)**
Ludwig-Maximilians University, Munich, Germany

Publications

Nawani J., Rixius J., & Neuhaus, B.J. (2016). Influence of using challenging tasks in biology classrooms on students' cognitive knowledge structure. *International Journal of Science Education.*

Nawani J., Kotzebue L., Rixius J., Graml M., & Neuhaus, B.J. (2017). Teachers' use of focus questions in German biology classrooms. *International Journal of Science and Mathematics Education.*

Nawani J., Kotzebue L., Spangler M., & Neuhaus, B.J. Co-constructing Scientific Explanations: A lesson-design Model. *Journal of Biological Education.* (**Second revision).**

Nawani J., Kotzebue L., & Neuhaus, B.J. Teachers’ use of constructivist learning design features in German biology classrooms (**In preparation).**

Nawani J., Kotzebue L., Spangler M., & Neuhaus, B.J. Designing explanation oriented inquiry learning environments: A pre-service teacher support program (**In preparation).**

Posters & Presentations

Nawani J. (2017, January). Teaching Effectiveness in Biology Classrooms. Presentation given during the event 'Doctoral Training Programme: Research Colloquium - 2017', Munich Centre of the Learning Sciences, Ludwig-Maximilians-Universität München (LMU), Germany.

Nawani J., Rixius J., Neuhaus, B. J. (2016, July). Use of Scientific Reasoning Tasks in Biology Classrooms. Presentation given during the international workshop 'Interplay of Domain-Specific and Domain-General Aspects of Scientific Reasoning and Argumentation Skills - 2016'. Centre for Advanced Studies, Ludwig-Maximilians-Universität München (LMU), Munich, Germany.

Nawani J. (2015, June). Teaching Effectiveness in Biology Classrooms. Presentation given during the event 'Doctoral Training Programme: Research Colloquium - 2015', Munich Centre of the Learning Sciences (MCLS), LMU, Germany.

Nawani J. (2015, March). Use of Scientific Reasoning Tasks in Biology Classrooms. Poster presented during the 'REASON Spring School – 2015', Ludwig-Maximilians-Universität München (LMU), Germany.

Nawani J. (2014, June). School education scenario in India and key findings from investigating German biology classrooms. Presentation during the event 'Seminars on Teacher Education Research – 2014'. Institute of Biology Education, Ludwig-Maximilians-Universität München (LMU), Germany.

Nawani J., Rixius J., Graml M., Neuhaus, B.J. (2014, April). Focus Questions in Biology Classrooms. Poster presented at the 'Scientific reasoning and argumentation Retreat – 2014', Organized by REASON doctoral school, Munich, Germany.

Nawani J. (2014, February). Focus Questions in Biology Classrooms. Presentation during the event 'Doctoral Training Programme (DTP): Research Colloquium –2014. Organized by ‘Munich Centre of the Learning Sciences (MCLS)’, LMU, Germany.

Nawani J. (2013, June). Educational Scenario in India: Spotlight on the teaching scenario in Indian classrooms. Seminars on teacher education research – 2013, Institute of Biology Education, LMU, Germany.

Scholarships/ Grants Awarded

DAAD –STIBET international doctoral students mentoring grant:
Ludwigs-Maximilians University, International Office, Germany -2017

Doctoral completion grant:
Ludwigs-Maximilians University,Graduate Center, Germany -2016

Doctoral exchange fellowship:
Center for International Mobility (CIMO), Finland -2015

Doctoral study grant:
Federal Ministry of Education and Research (BMBF), Germany -2013

Declaration

The above information provided is true to my best of knowledge and belief

Jigna Nawani

Erklärung über die Eigenanteile bei Ko-Autorenschaft

Hiermit wird bestätigt, dass folgenden zwei Publikationen und folgendes Manuskript federführend von Frau Jigna Nawani im Rahmen ihrer Dissertation abgefasst wurden.
Dies geschah mit folgenden Anteilen:

Publication I

Nawani, J., Rixius, J., & Neuhaus, B. J. (2016). Influence of using challenging tasks in biology classrooms on students' cognitive knowledge structure: an empirical video study. *International Journal of Science Education*, *38*(12), 1882-1903.

Jigna Nawani has identified the underlying theoretical concept, identified the scientific problem and hypothesis, statistically evaluated the data, worked up the data for the publication, conceptualized the article, written it as a first author, and revised it critically as per the comments provided by the reviewers of the journal.

The co-authors developed the study design and the coding protocol and were included in the data acquisition. They coded the video data based on the coding protocol and participated in the development of the manuscript.

Publication II

Nawani, J., Kotzebue, L., Rixius, J., Graml, M., & Neuhaus, B. J. (2017). Teachers' Use of Focus Questions in German Biology Classrooms: A Video-based Naturalistic Study. *International Journal of Science and Mathematics Education*, 1-21.

Jigna Nawani has identified the underlying theoretical concept, identified the scientific problem and hypotheses, statistically evaluated the data, conducted the qualitative analysis, worked up the data for the publication, conceptualized the article, written it as a first author, and revised it as per the comments provided by the reviewers of the journal.

The co-authors developed the study design for the quantitative segment and contributed to the development of the coding protocol for the qualitative and quantitative data. They were included in the data acquisition and in the coding of the data. Furthermore, they participated in the development of the manuscript.

Manuscript I

Nawani J., Kotzebue L., Spangler M., Neuhaus, B.J. Co-constructing Scientific Explanations: A lesson-design Model. *Journal of Biological Education* (**Second revision).**

Jigna Nawani has identified the underlying theoretical concept, identified the scientific problem and hypothesis, developed the lesson-design model, designed the model lesson in collaboration with the grade 11 biology teacher, worked up the data for the article, written it as a first author, and revised it as per the comments provided by the reviewers of the journal.

The co-authors contributed to the development of the model lesson and the critical revision of the article as per the comments provided by the reviewers of the journal.

München, den 04.12.2017

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(Jigna Nawani)

München, den 04.12.2017

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(Prof. Dr. Birgit J. Neuhaus)

Eidesstattliche Erklärung

Ich versichere hiermit an Eides statt, dass die vorgelegte Dissertation von mir selbständig und ohne unerlaubte Hilfe angefertigt ist.

München, den 04.12.2017

…………………….

(Jigna Nawani)

Erklärung

Hiermit erkläre ich,

dass die Dissertation nicht ganz oder in wesentlichen Teilen einer anderen prüfungskommission vorgelegt worden ist.
das ich mich anderweitig einer Doktorprüfung ohne Erfolg nicht unterzogen habe.

München, den 04.12.2017

………………………….

(Jigna Nawani)