J Sci Teacher Educ (2009) 20:1–20
DOI 10.1007/s10972-008-9118-3

Developing Biology Lessons Aimed at Teaching for Understanding: A Domain-specific Heuristic for Student Teachers

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Published online: 18 October 2008

Abstract Teaching for understanding requires teachers to organize thought-demanding activities which continually challenge students to apply and extend their prior knowledge. Research shows that student teachers often are unable to develop lessons in teaching for understanding. We explored how a domain-specific heuristic can assist student biology teachers in developing problem-posing lessons according to teaching for understanding. Worksheets of lesson plans were analyzed according to criteria for problem-posing lessons. Furthermore, student teachers' perceptions of the design heuristic's usefulness were categorized in a cyclical process. In general, the heuristic appeared helpful to most student teachers for designing problem-posing lessons satisfactory according to the criteria. Furthermore, teachers indicated that using the heuristic deepened their subject matter knowledge and their awareness of pupils' prior knowledge.

Keywords Teaching for understanding · Problem-posing education · Biology teaching · Student teachers

Introduction

Reformers of science education criticize current educational practice that is based on a view of teaching as presenting content and learning as rehearsal and retention

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of presented information (e.g., Donovan and Bransford 2005; Wiske 1998; National Research Council (NRC) (2000); Millar and Osborne 1998; Bereiter 2002). Instead, they call for teaching for understanding, in which teachers and pupils engage in a discourse about important ideas and participate in problem-solving activities grounded in meaningful contexts. Teaching for understanding makes high demands on teachers' subject matter knowledge. In order to help pupils to understand important ideas in a discipline, teachers must have an in-depth understanding of these ideas, as well as of how these ideas relate to other ideas in the discipline (Gess-Newsome 1999; Grossman and Schoenfeld 2005; Abell 2007).

Rich subject matter knowledge is a necessary but not sufficient condition for teaching for understanding (Shulman 1986). Teachers must also be able to transform their subject matter knowledge into knowledge for teaching. Subject matter knowledge should be selected, ordered, and represented in ways that make it understandable for pupils. This is a difficult task because it is recognized that pupils do not simply copy the transmitted information, but construct knowledge on the basis of their prior knowledge (Borko and Putnam 1996). Therefore, the teacher cannot simply present the desired understanding to pupils. Instead, teachers have to design activities that stimulate pupils to extend or revise their prior knowledge toward the desired understanding.

We explored how student biology teachers can be supported in developing lessons according to teaching for understanding. Below, we first describe in more detail what we mean by teaching for understanding, in order to obtain a clearer view of how teachers should be assisted. We then briefly review research on knowledge that is needed for teaching for understanding and we introduce heuristics as means for lesson development. We present a domain-specific heuristic for developing biology lessons. We evaluated the usefulness of the heuristic for developing lessons in line with the requirements for teaching for understanding in a study among 15 student biology teachers. We conclude with some implications for teacher education and for further research.

Teaching for Understanding

Most educators agree that pupils need to acquire and use knowledge that goes beyond the rote memorization of facts. There is general agreement that pupils should *understand* subject matter. Understanding is an elusive concept, however, which can have diverse meanings for different people (NRC 2000; Blumenfeld et al. 1997; Bereiter 2002). We followed Perkins' performance view on understanding (Perkins 1998), according to which understanding a topic of study is a matter of being able to perform in a variety of thought-demanding ways on the topic, for instance, to explain, muster evidence, find examples, generalize, apply concepts, analogize, or represent in a new way. Such performances, which are often challenging problems, requiring pupils to go beyond the information given and to create something new building on what they already know, are called 'understanding performances'.

Given this performance perspective on understanding, how can teachers stimulate pupils to learn with understanding? Perkins (1998) compares learning with understanding with learning how to roller skate. Reading instructions and watching others may help, but is not enough. You learn to roller skate by skating. The same is true of understanding. If understanding a topic means building up performances of understanding around that topic, the mainstay of learning for understanding must be actual engagement in those so-called 'understanding performances'. According to Perkins, learners must spend the larger part of their time on activities that require the solving of problems which challenge them to apply and extend their prior knowledge. Merill (2002) has shown that this view of teaching and learning in which students demonstrate and develop their knowledge through a progression of increasingly complex problems is advocated not only by Perkins but also by many other influential modern instructional design theorists, for example, in the cognitive apprenticeship model (Collins et al. 1989), goal-based scenarios (Schank et al. 1999), constructivist learning environments (Jonassen 1999), and Elaborations theory (Reigeluth 1999).

The concept of understanding outlined above implies that an important task for the teacher in teaching for understanding is to develop a sequence of understanding performances for pupils. Engaging pupils in scientific investigations and problem solving, as well as designing a progression of problems for pupils, is difficult for teachers (Crawford 1999; Wiske 1998; Perkins and Unger 1999). The selected problems should be both approachable and challenging for students (Perkins 1998). Moreover, the pupils should be motivated to solve the problems. No challenging problem can be mastered without engagement. Klaassen developed an approach to teaching and learning in accordance with teaching for understanding as described above, which specifies how understanding performances (e.g., problems) should be sequenced in order to be motivating, approachable, and challenging for pupils (Klaassen 1995; Lijnse and Klaassen 2004). Klaassen argues that problems play an important role in providing pupils with motives for subsequent learning. He suggests that pupils are motivated for subsequent learning when they come to see the problems a teacher poses as their own problems. Therefore, problems should be selected and sequenced in such a way that solving one problem leads to the next problem and so on, until pupils arrive at the desired understanding. These problems are not presented to pupils as such; instead, the teacher must carefully devise activities in such a way that pupils come to phrase the problems themselves and thus come to see the intended problems as their own problems. For this reason, Klaassen called his approach to teaching for understanding a 'problem-posing approach'. During the process of solving and posing problems, pupils not only extend and revise their existing knowledge; they also come to understand the acquired knowledge as an adequate way to solve a problem. They learn for which type of problem this knowledge is a solution, and are able to provide arguments why this solution is better then some other alternatives examined.

In this research, we used the problem-posing approach as a means for assisting student biology teachers in developing lessons in line with teaching for understanding. We expected student teachers to develop a sequence of problems and activities arranged in such a way that solving a problem would lead to a new problem as long as the pupils had acquired the desired knowledge. We refer to such a sequence of problems and activities as a 'problem structure'. Developing such a problem structure is not easy. Research has shown that student teachers' lessons are often more in accordance with the transmission approach (Tobin et al. 1994; Borko and Putnam 1996). When planning instruction, teachers often overly rely on textbooks as opposed to pupils' understanding as an appropriate point of departure for the lesson. Textbooks often start by presenting knowledge and, subsequently, problem applications of this knowledge are presented in order to determine whether pupils have understood the knowledge (Tobin et al. 1994; Borko and Putnam 1996; Abell 2007). During lessons, most time is normally spent on learning facts and algorithms. Low-level questions predominate in the lesson. The teacher is often unable to connect pupils' comments and questions to the formal lesson and also often rejects unusual student answers. Thus, the question arises: how to assist teachers in developing problem-posing lessons. We elaborate on this question in the following section.

How to Assist Teachers in Developing Problem-posing Lessons

From Klaassen's (1995; Lijnse and Klaassen 2004) conceptualization of problem-posing education outlined in the former section it follows that two knowledge areas are important to teachers when developing teaching for understanding. First, developing a problem structure requires teachers not only to have adequate knowledge of the topic taught, but also to have thorough understanding of this knowledge as a solution to a certain problem, and of why this knowledge solves this problem better than some alternatives. Second, in order to develop problem-posing lessons, teachers also need knowledge of pupils' prior knowledge in order to be able to help them to see problems as their own and to guide them in the desired direction.

Research on pedagogical content knowledge (PCK) offers general guidelines for developing teachers' knowledge for teaching about specific topics. Twenty years ago, Shulman (1986, 1987) initiated research into teachers' knowledge needed for teaching specific subjects, which he referred to as 'pedagogical content knowledge' (PCK). According to his conceptualization, PCK was topic specific and included two subcategories: (1) knowledge of various representations of subject matter knowledge and (2) knowledge of pupils' difficulties in acquiring that knowledge and teaching strategies for overcoming them. Elaborating on Shulman's work, various authors have proposed different conceptualizations of PCK in terms of knowledge and beliefs categories needed to develop PCK for a topic, like subject matter knowledge, knowledge of learners, knowledge of instructional strategies, knowledge of the curriculum, and knowledge of assessment methods (see Van Driel et al. 1998; Hashweh 2005 for reviews).

Hashweh (2005) used a conceptualization of the content and development of teachers' PCK as a collection of basic units of what he called 'teacher pedagogical constructions'. These pedagogical constructions comprise knowledge on teaching a specific topic, such as photosynthesis. The pedagogical constructions are largely the result of the interaction between different types of teacher knowledge and beliefs, for example, subject matter knowledge, aims, knowledge and beliefs about learning and learners, and curricular knowledge.

Most PCK research does not focus on the development of these pedagogical constructions, but on mapping the *underlying* knowledge that is needed in this respect. Thus, the question arises how student teachers can be supported in developing problem-posing lessons. Hashweh contends that pedagogical constructions grow mainly during lesson-planning activities:

> I claim that they (pedagogical constructions, F.J.) result initially, and most importantly, from teacher planning, which is essentially a design process […] The resulting plan, whether mental or written, is a construction, not as tangible as the end-product of an architectural design process, but a construction none the less. Lately, many educators have accepted constructivism as an orientation, and have described learning as a constructivist process. If anything among all teacher knowledge categories is truly constructed, it is definitely the PCK category. Of course, these constructions are further developed as a result of interactive teaching and post-active reflection. (Hashweh 2005, pp. 278–279)

Research into lesson planning is scant in the PCK tradition (Hashweh 2005). Some research has been conducted into indirect methods for assisting PCK development, for example, lesson observations and teachers' own research into pupils' misconceptions (De Jong et al. 1998). In the teacher-thinking tradition, research has been conducted into lesson planning, but this research did not focus on content-related aspects of teaching (Clark and Peterson 1986). In the context of teaching for understanding, and more particularly problem-posing education, research into lesson planning has also received little attention. Existing schemes for planning lessons in teaching for understanding, such as the Teaching for Understanding framework (TfU) (Wiske 1998; Perkins and Unger 1999) and the framework of Wiggins and McTighe (2005), do not provide teachers with much assistance in developing problem-posing lessons for a certain subject matter area, such as biology. Below, we illustrate how we used a general idea in biology (organism as optimal design) to develop a domain-specific heuristic that should assist teachers in developing problem structures for biology lessons aimed at teaching for understanding.

Toward a Domain-specific Heuristic for Developing Problem Structures on Biological Topics

As it was our aim to support student biology teachers in developing problem-posing lessons, we turned to biology as a discipline. The rationale behind this was that, for student teachers to develop problem structures, they need to understand their knowledge of a certain biological system (e.g., the heart or the immune system) as an adequate solution to a certain problem. This implies that teachers have to rebuild their knowledge structures by posing and solving problems. But how can they be assisted in creating problems and solutions? Research into domain-specific heuristics as tools for pupil learning is promising in this respect. A domain-specific heuristic is based on general ideas of the subject at hand, and is used to guide pupils in a certain direction during the framing and solving of problems (Perkins and

Salomon 1989; Alexander et al. 1998). This is in line with Schwab (1962), who already stressed the importance of domain-specific methods for developing pupils' knowledge in the sixties. In earlier research, we developed such a heuristic for stimulating pupil learning in biology lessons (Janssen 1999). Such a heuristic might also help *teachers* in formulating and solving problems when planning their lessons. Such a domain-specific heuristic for teaching has not yet been described in the literature (Janssen and Verloop 2003).

In biology, a frequently used heuristic is that based on the idea of organisms as optimal designs. For centuries, people have been astonished by the adaptations found in nature (Gould and Lewontin 1979; Williams 1996). Organisms seem to be optimally designed for survival and reproduction in their natural habitats. In modern biological research, the idea of optimal design fulfils a heuristic function for developing new knowledge. In the so-called adaptationist program in evolutionary biology, this idea is applied to investigate the function for which a certain trait is selected (Gould and Lewontin 1979; Ridley 2004). Researchers aim to discover the function of a trait by redesigning it.

Several steps can be distinguished in redesigning a biological system (Parker and Smith 1990; Ridley 2004). First, the researcher tentatively formulates the design problem (the function) to which the trait in question is a solution. Then, some alternative, biologically possible, solutions are generated. The disadvantages for survival and reproduction of every alternative are listed. This is followed by qualitative or quantitative determination of the optimal solution to a given problem. When the optimal solution corresponds to the observed trait, it is concluded that the design problem is understood. When the optimal solution does not correspond, it is concluded that the design problem, the set of possible solutions, and/or the disadvantages were wrongly estimated. The procedure must then be repeated using different assumptions.

An important issue using optimization theory is deciding which biological structures or strategies are possible and what constraints apply. The assumption by adaptationists is not that existing traits are "perfect" (e.g., unbreakable bones without mass), but that they contribute more to reproductive success than the alternatives that existed in past populations. Since variation in nature is limited by evolutionary, developmental, genetic, and physiological constraints, natural selection cannot lead to perfect traits. It can only select traits that are optimal with respect to a domain of biologically possible variation. Many constraints are not known in advance, but can be discovered by formulating a hypothesis and testing predictions against observations. If the predictions do not match observations, we can have overlooked constraints that arise, for instance, from the organism's ancestry. We then should try another hypothesis, starting from different assumptions.

We expected that it would be possible for student biology teachers to apply the design heuristic independently to develop problem structures for teaching particular biological systems. It was necessary to adapt the heuristic for this purpose. The heuristic is first needed for developing adequate subject matter knowledge. Therefore, we needed to find out what type of knowledge must be acquired and what relevant prior knowledge of biological systems is normally possessed by student biology teachers. Generally, teachers are familiar with the design problems

Table 1 A design heuristic for student biology teachers

1. Determine the function of the system as a whole
2. Reformulate this function as a design problem
3. Devise one or more solutions to this problem
4. Consider possible disadvantages of the solutions
5. Identify the solution with the fewest disadvantages
6. Go back to step 3

of the system as a whole. They know, for instance, the functions of a muscle or the kidney. They also know more or less how the system works. However, they do not always grasp which design problems are fulfilled by specific parts of a system. They also may not know why a given part is a better solution than an alternative (Janssen 1999). On the basis of this information, we constructed the design heuristic presented in Table 1 for student biology teachers consisting of six steps.

We describe below how this design heuristic can assist student biology teachers in developing problem structures for lessons according to teaching for understanding. Two phases can be distinguished. In the first phase, student biology teachers use the design heuristic to extend and, if necessary, adjust their knowledge of biological systems. In the second phase, this tentative problem structure is adapted to the prior knowledge of pupils in a lesson plan.

In the first phase, in order to redesign a biological system, the teacher uses the design heuristic. The first step is to identify the function of a system as a whole. For instance, the function of the heart is the circulation of blood. In the second step, this function is reformulated in a design problem (how to circulate blood in the body). Subsequently, one or more alternative solutions and their disadvantages are formulated (steps 3 and 4). The solution with the least number of disadvantages is selected and reformulated in a design problem (steps 5 and 6), and so on. The textbook can be consulted to check alternative solutions. When teachers redesign a biological system they come to understand biological knowledge as an adequate attempt at solving problems (Janssen 1999). Not only do they know the problems for which the knowledge is a solution, they also know why this solution is better than some alternatives. The first phase not only results in a richer understanding of certain biological systems, but it also leads to the first tentative sequence of problems and solutions (a problem structure) for teaching the system (see Table 2).

In the second phase, the tentative problem structure developed needs to be adapted to the prior knowledge of pupils in lesson plans, since the initial problem structure is based on the teachers' prior knowledge. We aimed at developing a problem structure in which pupils themselves would phrase the main problems and, in that way, view the intended problems as their own problems. For every problem, therefore, it must be determined whether the pupils would be able to arrive at the same solution and corresponding disadvantages. The design heuristic can be used for this task. First, teachers use the heuristic to devise more solutions and disadvantages. They then determine which prior knowledge pupils need to devise the same solution and disadvantages. For example, in order to discover the disadvantages of blood vessel contraction with valves, pupils need to know, at least, that cells need to take up oxygen from the blood and that blood is oxygenated in the

Table 2 The design heuristic applied to redesigning the heart

System: heart Function: blood circulation		
Design problem	Solution	Disadvantage
1. How to circulate blood in the circulatory system?	1. Blood vessel contraction	1. Blood can flow both ways
2. How to make sure that blood circulates in only one direction?	2. Blood vessel contraction with *valves*	2. Oxygenated blood from the lungs and deoxygenated blood from the rest of the body are mixed together
3. How to prevent mixing?	3. Divide the blood vessel into two compartments (*the heart is divided into right and left parts*)	3. Blood pressure is limited because the blood vessel must first be full before blood can be pumped through the body
4. How can the blood pressure be raised?	4. Let blood first be sucked into a special compartment (*the atrium*) and subsequently be injected into another compartment that contracts (*the ventricle*). (*The result is a heart containing two atria and two ventricles*)	4. The heart muscle itself is not provided with oxygen

Scientific names of solutions that correspond to textbook knowledge are printed in italics

lungs. When a teacher expects that the students possess the knowledge they need, he or she can predict that at least some of the pupils will come up with the same solution and disadvantages as the teacher. When a teacher expects that pupils lack the knowledge they need, he or she has to consider when and how to provide additional information, which will result in minor or major adaptations of the problem structure. In some cases, it is enough to provide pupils with a hint while they are solving the problem. Sometimes, however, the problem needs to be split into several sub-problems to allow pupils to solve it, and in some cases extra problems need to be solved before they can solve that particular problem. For example, when pupils do not know the circulatory system, they have to design the system before they are able to design a heart that pumps blood through the system.

Below, we describe a study in which we explored the usefulness of this domain-specific design heuristic for developing problem-posing lessons aimed at teaching for understanding by student biology teachers. We investigated whether the design heuristic actually stimulated the student biology teachers to develop problem structures for biology lesson plans that were in line with teaching for understanding according to the problem-posing approach, and we examined the participants' perceptions of the usefulness of the design heuristic. The research questions were the following:

1. To what extent does the design heuristic enable student biology teachers to develop problem structures for biology lesson plans that are in line with problem-posing education?

2. What benefits and drawbacks do the student biology teachers experience while using the design heuristic for developing problem structures and lesson plans?

In the next section, we describe how we tackled the research questions using student biology teachers' initial lesson plans and their new lesson plans after redesigning a biological system.

Methodology

Context and Participants

The current study was conducted in the context of a graduate school of teaching. Fifteen student biology teachers volunteered to participate in the study. Their age varied from 24 to 30 years. The student biology teachers all had a master's degree in the life sciences when starting their teacher education. They where specialized in different areas of the life sciences (ethology, animal physiology). During 1 year, they attended working classes on Mondays. The rest of the week they taught at an internship school. On average, the participants taught six biology lessons each week. At the time of data collection, the student biology teachers had approximately 6 months of teaching experience. They were not familiar with the design heuristic. This was introduced to them by a teacher trainer who was knowledgeable on the subject of biology teaching.

Procedure

Six steps were taken to make participants familiar with the design heuristic and have them use the heuristic for planning lessons (Table 3).

The student biology teachers planned a lesson twice for the same biology topic. They were asked to select a topic they intended to use in a forthcoming lesson and which met two criteria: (1) they considered themselves knowledgeable on their topic of choice; and (2) it was part of the biology curriculum. They made a lesson plan first without using the design heuristic, and then using it (see Table 3 for the time

Table 3 Steps in the procedure for familiarizing student teachers with the design heuristic and having them use the heuristic to plan lessons

Step 1	Student teachers develop a lesson plan for a self-selected biological system without the design heuristic (worksheet 1) (60 min)
Step 2	Teacher trainer demonstrates the use of the design heuristic for the subject immunology (20 min)
Step 3	Student teachers try out the design heuristic by redesigning the heart (45 min)
Step 4	Student teachers redesign their self-selected biological system (step 1) using the design heuristic (worksheet 2) (60 min)
Step 5	Student teachers translate their redesigned system into a lesson plan (worksheet 3) (60 min)
Step 6	Student teachers report the benefits and drawbacks experienced while working with the design heuristic (worksheet 4) (20 min)

schedule). The two lesson plans were compared using the design heuristic. The student biology teachers were not familiar with the heuristic in advance; they were familiarized with it using the cognitive apprenticeship model (Collins et al. 1989). After the first lesson plan had been developed, the teacher trainer introduced the design heuristic. First, by encouraging them to think aloud and using the immune system as an example, student biology teachers were taught how to use the heuristic. They were then given the opportunity to try out the design heuristic by redesigning the heart. The teacher trainer provided them with feedback. Afterward, the student biology teachers used the design heuristic to make a lesson plan for the self-selected topic. During making these lesson plans, no supervision was provided by the teacher trainer. Finally, the student biology teachers were asked to report the benefits and drawbacks they experienced when working with the design heuristic. Worksheets filled out by the student biology teachers during steps 1, 4, and 6 were used for data collection.

Analysis

The worksheets that represented the first and second lesson plans were collected in steps 1 and 5 (Table 3) were analyzed according to a list of criteria for problem structures in order to evaluate the usefulness of the design heuristic (Table 4). These criteria were derived from Klaassen's ideas on problem-posing education (Klaassen 1995; Lijnse and Klaassen 2004). Klaassen's criteria have been formulated for PhD design research projects which last 4 years. Since our student biology teachers only had 1 h to develop a problem structure, we alleviated the rigor of Klaassen's criteria for the purpose of this study. First, in order to have a problem structure, we expected teachers to elaborate more than two problems. In addition, as a general criterion, we stated that problems had to be selected and ordered in such a way that solving and testing one problem would raise new problems, until pupils acquired the desired knowledge, and to stimulate students to extend and revise their existing knowledge. Furthermore, we wanted student biology teachers to think of multiple solutions to problems and their disadvantages in order to make pupils understand the acquired knowledge as an adequate attempt at solving a problem. Finally, in order to stimulate pupils to come to see the intended problems as their own problems, expected solutions and disadvantages had to match with pupils' prior knowledge in terms of assumed pupil responses in at least half of the cases.

The analysis of the lesson plan sheets was done in three steps. First, two teacher trainers who were knowledgeable on the subject matter areas analyzed the lesson plans independently of each other according to the criteria in Table 4. Second, the

Table 4 Criteria for analyzing the problem structures in lesson plans

1. The problem structure consists of more than two problems
2. The solution of one problem leads to another problem
3. For at least half of the problems, multiple solutions are formulated
4. Expected solutions and disadvantages match with pupils' prior knowledge in terms of assumed pupil responses in at least half of the cases

analyses by the two teacher trainers of each lesson plan were compared. In four cases, interpretations did not match, and these were discussed. Agreement was easily reached.

The worksheets filled out in step 6 were analyzed in order to evaluate teachers' perceptions of the design's usefulness. Teachers' reactions were calculated and categorized into benefits and drawbacks of using the design heuristic. Categorization was performed in a cyclical process focused on further developing the system of categories (cf. Straus 1987). During the cyclical process, we grouped the benefits and drawbacks and in the process, some subcategories emerged from the data.

Results

Evaluation of Problem Structures in Lesson Plans

Table 5 shows the results of the analysis of the lesson plans. It is clear that, in most cases, the lesson plans that were made without the design heuristic are not problem-posing. These lesson plans often follow a traditional approach to teaching: They start by presenting knowledge and then provide assignments in which students have to apply the presented knowledge. One student biology teacher did, however, develop a problem-posing lesson without the design heuristic for the topic of joints. The lesson plans that were developed using the design heuristic all consist of more than two problems, except for one. Furthermore, in two-thirds of the new lesson plans, the solution of one problem leads to another problem. However, only six lesson plans meet the third criterion, according to which multiple solutions must be formulated for at least half of the problems. Finally, in almost two-thirds of the lesson plans, the expected solutions and disadvantages matched with pupils' prior knowledge in terms of assumed pupil responses.

In order to illustrate these findings, we present below two representative examples of lessons on the eye by one student biology teacher (Peter); one without and one using the design heuristic.

In the lesson plan in Table 6, the features of a traditional lesson method in which knowledge is transferred to students can be recognized. Peter first presents the knowledge to the pupils and subsequently asks them to apply or test the knowledge.

Table 5 Evaluation of lesson plans according to criteria for problem-posing education ($N = 15$)

Criterion	Lesson plan without design heuristic	Lesson plan with design heuristic
1. The problem structure consists of more than two problems	1	14
2. The solution of one problem leads to another problem	1	10
3. For at least half of the problems multiple solutions are formulated	1	6
4. Expected solutions and disadvantages match with pupils' prior knowledge in terms of assumed pupil responses in at least half of the cases	2	9

Table 6 Peter's lesson plan without design heuristic (worksheet 1)

Teacher activity	Pupils' activities
Tells students that eyes are meant to see	Listen
Explains the elements of the eye using the movements of light rays	Listen and answer each question
Eyeball	
Pupil (possible function?)	Arranging the light
Lens	
Retina (sensorial cells)	
Eye nerves to the brains	
Gives students the assignment of naming the function of each element in the book	Complete the assignment

Table 7 Redesign of the eye by Peter

System: eye		
Function: orientation		
Design problem	Solution	Disadvantage
How do people observe their environment?	With light sensitive cells (sensorial cells)	You see where the light comes from but you don't have a view
How can observations be improved?	Light-sensitive cells in a little bowl	You don't have a clear view because too much light comes in
How can the amount of light that comes in be decreased?	Reduce the aperture	Reducing the amount of light makes you see less
How can more light be admitted without blurring the view?	With a lens in front	Too much light causes blindness; too little light makes it dark
How can incoming light be kept stable when the amount of light that comes in from outside varies?	Make the aperture variable: for a large amount of light, small; for a small amount of light, large	

Table 7 shows how Peter redesigned the eye using the design heuristic to construct his knowledge of the eye step by step, reformulating the disadvantage of the solution to one problem as a following problem.

Table 8 shows how Peter translated the redesigned system into a lesson plan. While planning the lesson, he continually chose either himself or the pupils to give the answers. He also inserted assignments into the lesson plan in order to clarify or demonstrate certain aspects. The result is a lesson plan that differs considerably from Peter's initial plan. In the initial plan, Peter presents the knowledge to the pupils without explicating the underlying problems. In the new, problem-posing lesson plan, the lesson starts with a problem that leads to a disadvantage which functions as a next problem. In this way, the eye is redesigned step by step. One

Table 8 Peter's lesson plan after redesign of the eye (worksheet 3)

Teacher activity	Pupils' activities (including assumed responses)
What happens when you have your eyes closed?	You don't see anything
You have eyes to be able to see and find the way	
What is the easiest way to find the way?	If you know where light comes from
How?	
Proposes a spot (retina) with sensorial cells that are able to see light	A spot that is able to observe light
What is the disadvantage?	You don't have a view
How can you adapt this system in order to improve your view somewhat?	Students view an object first through a small hole in a piece of paper, then without the paper, and then through the hole again.
Students receive an assignment (right column)	
Teacher asks the question again	If the senses catch less light, you have a better view
	Still not sharp, because a lens is not available
So, yes, it is possible to enclose your senses in a small bowl (eyeball)	Too little light comes in, especially when it is dark
What is the disadvantage?	
Now we put a lens in front, does it solve the disadvantages? Explain your answers.	The lens makes it possible for the hole to be bigger because the light rays go in one direction. That is why you have more light.
What is a possible disadvantage?	Too much light causes blindness
How can you avoid becoming blind?	Watch your neighbour's eyes. He holds his hands in front of his eyes for a moment and takes them away (what changes do you see?) The pupil decreases.
Students receive an assignment (right column)	
	You can arrange the light with your pupils.
Was this enough? Do we have a sharp view now?	Yes
No, because the brain has some processing to do. This is done by the eye nerves.	
Students receive an assignment (right column)	Describe how the light comes through your eyes, which way it goes, and what happens there.

element is taken by Peter from the initial lesson plan: how the light goes through the eye and the way it goes. In the original lesson plan, Peter informs the pupils on this matter. In the new lesson plan, pupils have to solve this problem themselves by doing an assignment. Peter's lesson plan met all criteria reasonably well, except criterion 3, for most problems only one solution is formulated.

An example from another student biology teacher shows that it is sometimes difficult to meet criteria 2 and 4. When redesigning the bee dance, one teacher came to the conclusion that the function of the system is to show both the direction and distance to other bees that are looking for honey. This is an example of a biological system in which two problems do not follow from one another (criterion 2), but exist simultaneously. It is difficult to make a sequential problem structure for such systems. Moreover, in this case, the same student biology teacher often overestimated the prior knowledge of pupils. He expected for instance that pupils would be able to find the correct solution to the direction problem. To solve this problem, pupils would need to know exactly where the bee dance is taking place. We can not expect that pupils possess that knowledge already. Thus, in this case the expected solution does not match with pupils' prior knowledge (criterion 4).

Benefits and Drawbacks Reported by the Student Biology Teachers of Using the Design Heuristic

Table 9 presents the benefits of using the design heuristic reported by the student biology teachers. These advantages may be categorized into three subcategories of benefits: (1) subject matter knowledge; (2) knowledge of pupils; and (3) teaching methods.

The first subcategory comprises benefits with respect to subject matter knowledge. Benefits reported in this subcategory include more thorough knowledge of the main elements of which a biological system is built and why it is organized as it is, activating and adjusting prior knowledge, and learning new things. Second, the student biology teachers reported benefits with regard to knowledge about pupils. By translating the redesigned system into a lesson plan and formulating problems, the student biology teachers found that they improved their insight into pupils' prior knowledge and possible difficulties that pupils might experience when answering questions. Third, the student biology teachers reported positive expectations about the possible effects of their new lesson plans compared to the original ones. The student biology teachers expected a problem-posing lesson to improve pupils' motivation, and more active engagement with the subject matter taught. Furthermore, many student biology teachers considered it an advantage that they were less dependent on books.

The student biology teachers also reported difficulties in using the design heuristic (Table 10). Reported drawbacks may be subcategorized into categories

Table 9 Benefits reported by student teachers of using the design heuristic ($N = 15$)

Subject matter knowledge	
You learn why the system is organized as it is	15
As a teacher, you improve your ability to distinguish matters of major and minor importance in the system	7
Your own prior knowledge is activated and adjusted if necessary	11
You learn a lot of new things	10
Knowledge about pupils	
You get insight into relevant prior knowledge of pupils	10
You improve your insight into what pupils find difficult	9
Benefits concerning the teaching method that teachers developed by using the design heuristic	
You are less dependent on the book	8
Your lessons match better with pupils' prior knowledge	11
As a result of departing from pupils' problems, they are more motivated	14
Pupils' understanding of subject matter improves	15
Pupils learn why a biological system is organized in a certain way	8
Pupils are more actively involved in the lessons	15

Table 10 Drawbacks reported by student teachers of using the design heuristic ($N = 15$)

Redesigning a system	
Sometimes it is difficult to think of a question which is partly a solution	12
Sometimes you have to depart from your own knowledge of a system to think of alternatives, and that is difficult	12
Sometimes it is difficult to think of disadvantages because they are not mentioned in books	11
Sometimes one problem doesn't follow logically from the previous problem by a disadvantage, and then a new problem is tackled	6
Making lesson plans using the redesigned systems	
It is not always clear which problems you should use to start	4
It is not always easy to estimate pupils' prior knowledge	7
It is not always easy to know if you can expect pupils to arrive at the desired answers from their initial answers	9
When do you tell the pupil how the system really is designed?	5
It takes more time than preparing a traditional lesson	15
How do you determine what you explain and what pupils have to do themselves?	3

that represent two phases in developing a lesson plan according to the design heuristic: (1) redesigning a biological system as a tentative problem structure; and (2) making a lesson plan according to the system designed.

Table 10 shows that most student biology teachers struggled with the problem that they knew the 'right answer', but found it difficult to find a question underlying that answer. Furthermore, a majority of the student biology teachers found it difficult to depart from their own knowledge of systems and to think of alternative solutions or disadvantages. Another drawback experienced by many student biology teachers was the large amount of time that had to be invested in developing lesson plans according to the design heuristic. Developing a problem-posing lesson plan is more time consuming than developing traditional lesson plans because teachers can use textbooks for the latter. However, the extra time investment turned out to be less than expected. The student biology teachers needed approximately 30 min to make their initial lesson plan without the design heuristic, and 40 min for the problem-posing lesson plan using the design heuristic.

Discussion

Teaching for understanding is an important educational vision which is shared in many educational reforms (Wiske 1998; Bransford et al. 1999; NRC 2000). It is, however, difficult for teachers to put into practice, and the problem-posing approach is particularly challenging. In the research reported above, we developed a domain-specific design heuristic for developing problem-posing lessons aimed at teaching for understanding by student biology teachers. In a study among 15 student biology teachers, we explored whether the design heuristic was helpful to student teachers in developing problem structures for biology lesson plans in line with problem-posing education. Furthermore, we gathered information on student teachers' perceptions of the usefulness of the design heuristic. In general, the results show that without the design heuristic, all student biology teachers except one followed a traditional approach in planning their lessons. This is in line with research that shows that student teachers' lessons are often more in accordance with transmission approaches to teaching (Tobin et al. 1994; Borko and Putnam 1996). Using the design heuristic stimulated the student biology teachers to develop problem structures in lesson plans which to a reasonable degree met the criteria for problem-posing education derived from Klaassen (1995; Lijnse and Klaassen 2004). All except one of the lesson plans that were developed by the student biology teachers after they redesigned a biological system consisted of more than two problems. Furthermore, solutions and problems are logically sequenced in two-thirds of the lesson plans, and expected solutions and disadvantages match with pupils' prior knowledge in terms of assumed pupil responses in at least half of the cases.

In one-third of the lesson plans, however, solutions and problems were not logically sequenced. Student teachers also reported this as a drawback of using the design heuristic. A more precise analysis of the lessons shows that, in three out of five cases, this would not even have been possible considering the nature of the system that was redesigned (see example of bee dance below Table 8). This matter should be explained to student teachers when introducing the design heuristic. Furthermore, only six student biology teachers were able to formulate multiple solutions for at least half of the problems. This is in line with the student teachers' reported drawbacks, which indicate that they found it difficult to formulate problems and alternative solutions and disadvantages. These findings might be explained by the fact that considering knowledge in a problem-posing way is a new way of thinking for teachers, since they often understand theories as facts and not as attempts at solving problems (Borko and Putnam 1996; Gess-Newsome 1999; Grossman and Schoenfeld 2005). Teachers are often more familiar with traditional approaches to teaching in which answers are presented to questions that are not made explicit. In two-thirds of the lesson plans, however, student teachers' solutions match well with the expected prior knowledge of pupils in terms of assumed pupil responses. This is in line with the student teachers' reported benefits, in which two-thirds of them indicate that their insights into pupils' prior knowledge and difficulties had improved. Nevertheless, it appears from the reported drawbacks that many student teachers find it difficult to estimate pupils' prior knowledge and to find a way in which pupils can be stimulated to arrive at the desired answers from their initial answers. In most cases in which expected solutions and disadvantages did not match prior knowledge of pupils, the student teachers overestimated pupils' prior knowledge (see bee case for example). Moreover, the student teachers could not rely on their expertise with respect to pupils' prior knowledge, since they had not taught the topics using a problem-posing approach before. They reported in the benefits, however, that they expected pupils' motivation, active engagement, and understanding to grow. Furthermore, they reported improvement of their subject matter knowledge (e.g., structure of the system and activation of prior knowledge) and of their knowledge about pupils (e.g., insight into pupils' prior knowledge and difficulties in understanding). Based on the results discussed above, we conclude that the design heuristic evaluated in this research is a reasonably useful tool for assisting student biology teachers in developing problem-posing biology lessons. For further discussion of the results, we focus on two aspects in which the current study differs from existing research in the PCK tradition: (1) the accent on lesson planning; and (2) the use of a domain-specific heuristic for lesson planning.

Accent on Lesson Planning

Together with Hashweh (2005), we argue that lesson planning has received too little attention in the current PCK research. In most studies more indirect methods for PCK development have been used such as classroom observations and research on pupils' preconceptions (see De Jong et al. 2005 for an overview). The redesigned lesson plans and reported benefits in the current study provide insight into how the student teachers wanted to teach a certain topic. The results show that student teachers developed the pedagogical constructions shown in their lesson plans in the direction of the problem-posing approach. The lesson plans and reported benefits also indicate that the student teachers might indeed have improved their knowledge of the subject matter and their knowledge of the conceptions of pupils by planning their lessons according to the design heuristic.

This research has focused on pedagogical constructions as represented in student biology teachers' lesson plans. These pedagogical constructions in turn are largely the result of the interaction of different types of teachers' knowledge such as subject matter knowledge and knowledge of pupils' prior knowledge and difficulties. Although student teachers reported developments with respect to underlying knowledge types, it is difficult to draw certain conclusions with respect to this kind of knowledge development on the basis of this study. In order to gain more insight into the knowledge development underlying teachers' pedagogical constructions, these basic knowledge types and their development should be researched more directly. This can be done by using think-aloud techniques during lesson planning, stimulated recall techniques, and critical incident techniques (Hashweh 2005; Loughran et al. 2006). Since this study was restricted to the analysis of student teachers' lesson plans and reported benefits and drawbacks, the validity of the research with respect to student teachers' underlying knowledge development is limited. Further research should also focus on teaching practice and reflective evaluations on this practice on the basis of lesson plans according to the design heuristic. This is relevant because student teachers might adjust their problem structures and lesson plans following evaluations of teaching practice, for example, by comparing pupils' actual responses to expected pupil responses.

The Use of a Domain-specific Heuristic for Lesson Planning

We used a domain-specific heuristic for lesson planning in this research, derived from a heuristic used in biological research. This is new in the PCK tradition. It has long been argued that domain-specific methods are needed in education. However, this was done for the purpose of providing student teachers with the knowledge needed for assisting *pupils* in developing their knowledge (Shulman 1986; Borko and Putnam 1996; Gess-Newsome 1999; Abell 2007). This research has shown that such heuristics can also help *student teachers* to develop lesson plans that are in line with teaching for understanding in a problem-posing manner. This implies that domain-specific heuristics could play a central role in stimulating teachers to develop such lessons by reconstructing subject matter knowledge, and translating this knowledge into a problem structure with ordered problems and solutions. However, teachers need time to get acquainted with the heuristic, and further assistance is needed in making choices with respect to teaching strategies, teaching methods, assessment methods, etc. Thus, good supervision is necessary when first introducing a domain-specific heuristic to student teachers. Furthermore, teachers still need to make choices with respect to specific teaching and assessment methods.

As the current study was limited to a heuristic that can be used for biology education, we conclude with some practical advice concerning the further development of domain-specific heuristics for other domains. This is relevant to teaching practice because many teachers do not possess domain-specific heuristics (Gess-Newsome 1999; Borko and Putnam 1996), and for many subject areas, such heuristics have not yet been developed (Janssen and Verloop 2003). Two routes are possible for developing such heuristics: a normative and an empirical route. In this research, we used the normative route, in which ideas for a heuristic are derived from philosophical analysis of the nature of the subject (e.g., the organism as optimal design). In the empirical route, the actual inquiry processes of experts in a discipline are studied in order to derive ideas about how to frame and solve problems in the domain (e.g., Wineburg 2001). In both cases, the heuristics developed should be adjusted to knowledge and facilities within reach of the teacher to allow the teacher to consider problems and solutions. Developing domain-specific heuristics can have several advantages for teacher planning. First, they are often applicable to a larger number of topics in the subject area than the usual topic-specific guidelines that are often offered in PCK workshops. Second, these heuristics are often more powerful, and provide more guidance than more general planning models derived from general teaching-learning theories like teaching for understanding. Finally, in the longer term, such heuristics provide teachers with the opportunity to develop their knowledge and lessons independently (cf. Kinach 2002).

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