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Teaching strategies to promote concept learning by design challenges

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Abstract: This paper presents the results of a mixed methods study in which 6 student teachers and 2 teacher trainers took part, that investigated the teaching practice of Learning by Design (LBD) in depth. The study is part of a series of studies, funded by the Netherlands Organisation for Scientific Research (NWO), that aims to improve student learning, teaching skills and teacher training. LBD uses the context of design challenges to learn, among other things, science. Previous research shows that this approach to subject integration is quite successful but provides little profit on (scientific) concept learning. For this, a lack of (knowledge of) proper teaching skills is suggested as an important reason. Thus, when the teacher's role is better understood concept learning might be strengthened. For this, a theoretical framework of teaching guidelines was developed and from this point of view the LBD practice was studied. Qualitative and quantitative data revealed that stimulation of an ongoing learning process and explicit teaching strategies are crucial for concept learning.

Keywords: Learning by Design, Science, Technology, Concept learning, STEM, Teaching skills

Introduction

Science and technology have grown progressively denser in our personal lives. Unfortunately, international studies, e.g. ROSE (Sjöberg & Schreiner, 2010), ascertained a decreasing interest in and understanding of science and technology among juveniles, where the opposite is necessary to cope the modern world. Other studies indicate a holistic understanding of science and technology, through interdisciplinary teaching, may overcome this problem (Lustig et al., 2009; Osborne & Dillon, 2008; Rennie, Venville, & Wallace, 2012). Therefore, national governments like the United States, the United Kingdom, Australia, New Zealand and European countries aim for interdisciplinary science, technology, engineering, and mathematics (STEM) education (National Science and Technology Council, 2013; Office of the Chief Scientist, 2013; Office of the Prime Minister's Science Advisory Committee, 2011; Parliamentary Office of Science & Technology, 2013). In this context technology should be seen as the way humans solve practical problems and meet needs, what makes technological activity purposeful and goal-directed where combining knowledge (e.g. conceptual, procedural and strategic), skills (e.g. design, experimentation, craft) and equipment (e.g. tools, materials, machines) is used for succeeding (International Technology Education Association, 2007).

Many integrative approaches use design contexts to learn, among others, knowledge and practices: Design-Based Modeling (Penner, Giles, Lehrer, & Schauble, 1997), Engineering for Children (Roth, 2001), Engineering Competitions (Sadler, Coyle, & Schwartz, 2000), Project-Based Science (Krajcik, Blumenfeld, Marx, Bass, & Fredricks, 1998), Informed Design (Burghardt & Hacker, 2004), Design-Based Science (Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004) and Learning by Design (Kolodner, 2002b). The latter has been studied extensively from 1999 till 2003 and showed high student-involvement and, compared to non-LBD classes, significantly better collaboration skills, meta-cognitive skills and science skills. However, concept learning lagged behind (Kolodner, 2002b; Kolodner, Camp, et al., 2003; Kolodner, Gray, & Fasse, 2003) despite the fact, which will be discussed later, LBD theoretically provides a sound basis for this.

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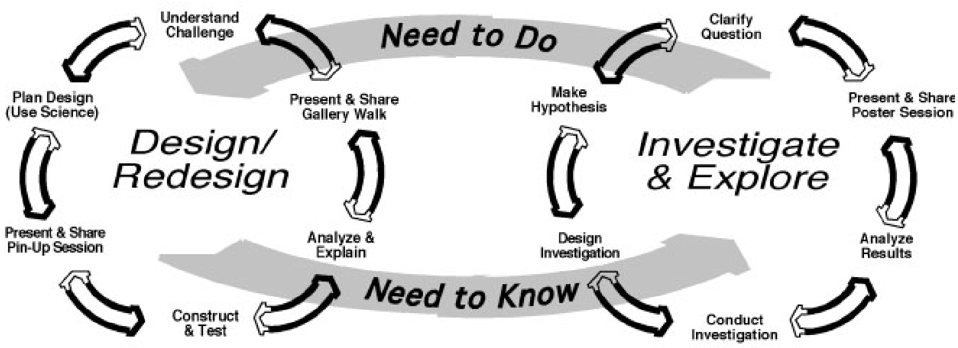
Back then, results were based on pre- and post-assessments. Therefore, because the LBD practice had less attention, prior to this study another study revealed how and when scientific content was addressed by students and what students learned from this (Van Breukelen, De Vries, & Schure, 2016). Results showed a strong product- and process-focus (What to do and deliver?) and students qualified scientific content (What to learn?) as tools needed for success. As a result mainly implicit learning of loose facts and incomplete concepts took place, where teacher-driven activities seemed to dominate concept learning (in a positive and negative way). This, along with the fact the teachers involved described task guidance as intensive and complex, asks for a deeper understanding of pedagogical teaching strategies for coping design-based science tasks. Therefore, this study explores these strategies and more specific the interaction with concept learning.

This necessity is supported by literature about learning and teaching that claims conceptual learning is highly teacher-dependent (Bamberger & Cahill, 2013; Van der Veen & Van der Wal, 2012). Using design faces teachers with an open-ended nature where teachers must relinquish directive control (Burghardt & Hacker, 2004). As a result, teachers leave or undermine LBD activities because they are not able to adjust to a new kind of classroom control (Wendell, 2008). Thus, teachers need help to develop proper pedagogical strategies (Bamberger & Cahill, 2013).

The practice of LBD

LBD is a project-based inquiry approach where students learn, among skills and practices, scientific content by achieving design challenges (Kolodner, 2002b). Figure 1 shows LBD is based on two main activities: design and investigation. Students use science practice (investigation) to achieve design challenges. For this, students (operating in design groups) have to explore the challenge resulting in things they need to know/learn for succeeding. By searching for information and conducting experiments they find answers to questions raised in order to apply them in the design. Investigation of this application may lead to additional questions and reinvestigation starts. To incentivize the understanding of design-related concepts, teacher-guided activities take place (poster and pin-up sessions, whole-class discussions and gallery walks). During these activities experiences and insights are shared among groups, feedback is being given and science is being made explicit. In short, students learn concepts and skills needed for success by identifying a need to learn them, trying them out, questioning their handling and thinking, and acting again (iteration). A more detailed description can be found in Kolodner, Camp, Crismond, Fasse, Gray, et al., 2003.

Figure 1
Learning by Design's Cycles



Note. Reprinted from Kolodner (2002b, p. 339)

Because concept learning is a main topic of this study it is important to explain how LBD aims for this. LBD provides a constructivist learning environment where students experience the necessity to learn (Kolodner, Hmelo, & Narayanan, 1996). This necessity is driven by the fact that students' pre-task conceptions are not sufficient for succeeding: design challenges deliberately address cognitive conflicts. Students need to develop a more scientific framework of knowledge to cope the conflicts and reach conceptual change (Abdul Gafoor & Akhilesh, 2013; Cobern, 1994). In compliance with Nussbaum and Novick (1982) and Cosgrove and Osborne (1985), LBD contains four main elements for conceptual change. First, students explore their pre-task conceptions (preliminary phase). Second, students become aware of their own and other's conceptual shortcomings (focus phase). Third, students investigate and explain the conceptual conflict (challenging phase) and, fourth, students adopt the new conceptual model (application phase). Based on literature, e.g. Brandsford, Brown, Donovan, and Pellegrino (2003), LBD contains several elements that promote conceptual change: collaboration, reflection, contextual learning, applying what is learned, learning from failures and iteration, and connecting skills, practices and concepts.

Research questions

As mentioned before, this study examines the interplay of teacher handling and concept learning. For this, the following research questions are leading: What teaching strategies are crucial for guiding LBD and, more specific, directive in helping students to learn (scientific) concepts?; To what extent these strategies are addressed during LBD?; Finally, which strategies should get more attention to promote concept learning?

Method

A design-based mixed methods study was used to face the research questions and 6 first-year student teachers (science) and 2 teacher trainers (principal investigators included) were involved. All participants had prior experiences on characteristic LBD components and student teachers had sufficient prior knowledge regarding the addressed science domain. The study was supported by a theoretical framework of (concept) learning-related teaching strategies deduced from literature. Based on this framework a LBD challenge was developed and performed. Quantitative data was used to examine students' concept learning. Qualitative data, complemented with a quantitative analysis, regarding the intensity of applied teaching strategies and students' views on the effectiveness of these strategies, revealed which strategies were directive to learn conceptual knowledge. Combining all data is was possible to establish which strategies should get more attention, aiming for better pedagogical strategies.

According to Crouch and McKenzie (2006) the qualitative framework and small number of participants (less than 20) requires the investigators to participate in the study. This enables investigators to establish continuing, fruitful relationships with participants and by theoretical contemplation to address the research problem in depth. Doing this the validity increases and drawing conclusions through analysis and induction is possible. Therefore, both investigators participated in the study by guiding the LBD challenge.

Design of the LBD challenge

The LBD task addressed the "direct current electric circuits" physics domain and two design groups were challenged to design a solar power system for a model house (Figure 2). The activity took 3 successive days (2 to 3 hours per day; 8 hours in total) and was guided by an instructive presentation and a students' and teachers' guide. To accomplish the task design specifications were given, shown in Table 1, that stimulated the use of underlying science, decision-making and creative thinking. Regarding design specifications and scientific objectives, shown in Table 2, the most fundamental design principles concerned proper wiring (combining series and parallel parts) and regulating current, voltage and resistance for maximum efficiency. Furthermore, common LBD stages and activities, shown in Table 3, were applied to guide the process and students were allowed to use digital learning resources.

Figure 2
Model house and layout

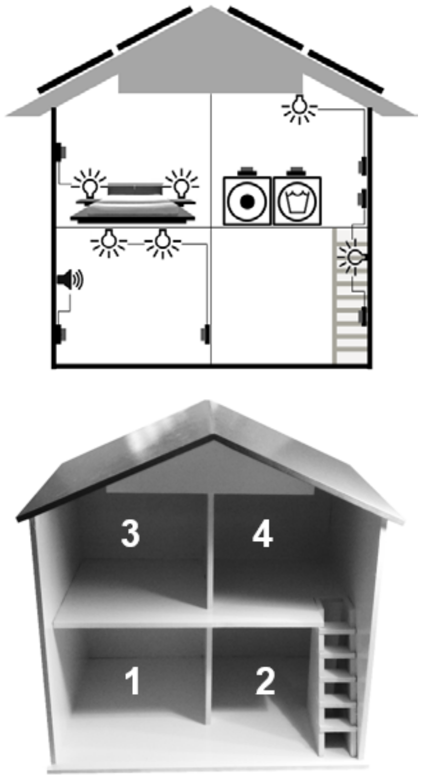


Table 1
Design specifications and components

Design specifications
A. [ROOM LAYOUT] Room 1: 2 lamps operated by 1 switch and a doorbell (SP) operated by 1 switch. Room 2: 1 lamp operated by a set of 2-way switches (staircase wiring). Room 3: 2 lamps operated by 1 switch. Room 4: 1 lamp operated by 1 switch, 1 washing machine (M2) with adjustable speed operated by 1 switch, 1 dryer (M1) operated by 1 switch.
B. [SOLAR POWERING] The entire lightning has to be connected to a separate (combination of) solar cell(s). The same applies to the doorbell and washer-dryer combination.
C. [EFFICIENCY] The energy efficiency of the entire wiring has to be as high as possible and, in addition, the use of materials as less as possible. In any case, it is not allowed to use more components than available.

Component	Quantity	Component	Quantity
Motor 1.5V DC (M1)	1	Solar cell 4V/35mA	4
Motor 3.0V DC (M2)	1	Solar cell 5V/81mA	4
Mini-speaker 800mW (SP)	1	Solar cell 0.5V/400mA	4
Set of LEDs, resistors, wires and switches	1	Solar cell 0.5V/800mA	4

Table 2
Scientific objectives and interrelatedness with the challenge

DC electric circuits objectives	Interrelatedness
1. PHYSICAL ASPECTS OF ELECTRIC CIRCUITS: resistance is a property of an object and hinders current flow (Ohm's Law); Equivalent resistance in series increases and in parallel decreases as more elements are added; the necessity of a closed circuit to enable current flow; interpret pictures, diagrams, symbols of a variety of circuits.	• Resistors are necessary to reduce current flow and a variable resistor is necessary to adjust the washing machine's speed. Furthermore, students have to interpret and design a variety of circuit parts in order to meet the requested wiring.
2. ENERGY AND POWER: apply the concepts of energy (dissipation, conversion and conservation) and power (work done per unit time) to a variety of circuits.	• Students have to establish the amount of energy supply and consumption by the designed circuit in order to reach maximum efficiency.
3. CURRENT: understand and apply conservation of current (Kirchhoff's point rule) to a variety of circuits; explaining the behaviour of an ideal current source. 4. POTENTIAL DIFFERENCE, VOLTAGE: the amount of current is influenced by potential difference; apply the concept of Kirchhoff's loop rule ($\sum V = 0$ around a closed loop); explaining the behaviour of an ideal voltage source.	• Combining series and parallel parts (solar cells and components) to meet design specification forces students to investigate and calculate current flow and potential differences. Furthermore, students have to investigate the behaviour of (combined) solar cells to get informed about differences compared to (well-known) voltages sources.

Table 3
Stages and activities

Stages [time]	**Activities**[1]	**Final products**[2]
1. Introducing the Challenge and Context [15-20 min]	Introduction of context, design challenge, activities, organisation, learning sources, time schedules, materials, objectives, etc.	
2. Understanding the Challenge, Messing About, Whiteboarding [50-60 min]	• Exploration of the challenge, context and objectives (G) • Writing down ideas, (research) questions and hypotheses (G): what to do and learn? • Whiteboarding: sharing results; feedback session (C)	Design diary stage 2 • Flip chart for whiteboarding (G)
3. Investigate & Explore, Poster Session [120-180 min]	• Formulate and distribute (scientific) research questions (C) • Discussion "fair test rules of thumb" (C) • Design and conduct experiments, collect data, conclude (G) • Presentation of results: poster session; feedback session (C) • Discussion about results and fair testing: redoing/adjustments (C/G)	Design diary stage 3 • Final research questions (C) • Fair test rules of thumb (C) • Laboratory notebook (G) • Experiment poster (G)
4. Establishing Design Rules of Thumb [20-30 min]	• Determination of design rules using experiment results (C) • Focus on the science content: science vocabulary and concepts (C)	Design diary stage 4 • Design rules of thumb (C)
5. Design Planning, Pin-Up Session [80-90 min]	• Devise, share and discuss design solutions: divergent thinking (G) • Poster: provisional design solution (G) • Pin-up session (posters): feedback session (C) • Adjusting and redoing until satisfied: final design solution (C/G)	Design diary stage 5 • Design posters (G) • Design sketch (G)
6. Construct & Test, Analyse & Explain, Gallery Walk [120-180 min]	• Prototyping: realisation of the design solution (G) • Testing the design: realisation of design specifications (G) • Gallery walk: determine shortcomings; feedback/reflection (C) • Adjustments of the design rules and design solutions (C/G)	Design diary stage 6 • Prototype design (G)
7. Iterative Redesign [50-60 min]	• Iteration of previous steps depending on decisions made (C/G) • Improving the design (G) • Final discussion about design solutions and scientific concepts (C)	Design diary stage 7 • Final design solution (G) • Final reflection (individual)

C = class activity or product; G = design group activity or product

[1] Available resources: electronic learning environment (ELE), smartphones, laptops, tablets, Microsoft Office ® software, internet access, materials and tools for design realisation, materials for conducting experiments

[2] Design diary (ELE-archived): reflections, feedback, process descriptions and pictures/movies. Bulleted lists are stage-specific.

Framework of teaching strategies

To gain insight into (concept) learning-related teacher strategies, literature on pedagogical strategies, teacher competences and STEM education was studied that resulted in a theoretical framework of cohesive elements. The guidelines should help teachers to take enough control of the learning environment by intervening when necessary and holding back when possible: sensitive assistance (Murphy & Hennessy, 2001).

Table 4, partially derived for the previous study (Van Breukelen et al., 2016), shows in agreement with Horton (2006) learning and teaching has three essential types of interaction. Within these interactions there are five categories where in each category several teaching skills matter. In this context, we distinguish between skills emerging during the activity induced by the intervening teacher (anticipatory skills: A) and skills important for construction and preparation of the activity (preparatory skills: P). Concerning the latter regarding this study: think-pair-share guided fixed moments of student collaboration; all materials and tools were available from start to finish; the design diary and LBD rituals forced students to reflect, to provide and receive feedback and to explicate (used) science; students had to make sketches and drawings; learning objectives were discussed explicitly; clear instructions (student's guide and instructive presentation) were used to guide each stage; the teacher's guide contained guidelines of how and when to make science explicit.

Table 4

Learning-related teacher strategies

Interaction	Learning-related elements and teaching guidelines
Student (to student) interaction	**[A] Collaboration**: sharing information enriches the learning process and promotes knowledge building (Parkinson, 2001; Roth, 1995). Sketching and drawing helps students to externalise and review ideas (Popovic, 2004; Roth, 2001). The presence of the construction materials and tools, necessary for design creation, stimulates peer discussion about scientific concepts (Murphy & Hennessy, 2001; Roth, 2001). ■ | P | Collaboration should be organised in advance by a fixed structure. ■ | A | Stimulate collaboration: the design group has to be the first point of call. ■ | A - P | Stimulate and (partially) obligate students to make drawings and sketches. ■ | A - P | Ensure the availability of materials and tools (and stimulate students to use them).
	[B] Reflection: reflecting on knowledge, skills, attitudes and feedback makes students aware of doing and thinking and stimulates to maintain strengths or make adjustments. Collaboration provides input for reflection (Roth, 1995). ■ | P | Provide learning tasks with fixed moments of well-structured reflection. ■ | A | Stimulate reflective thinking during guidance: ask questions that excite reflective thinking. ■ | A - P | Stimulate students to base future handling on reflection. ■ | A - P | Attend to the fact that reflection should focus on knowledge, skills, attitudes, failures and successes.
Student to teacher interaction	**[C] Teacher and peer feedback**: providing feedback and receiving peer and expert feedback is invaluable for teaching and learning. Constructive feedback, also important for self-reflection, provides insight into doing and thinking and reveals students' strengths and weaknesses (Kolodner, 2002a; Kolodner, Gray, et al., 2003). Constructive feedback is relevant, goal-directed, well timed, behaviour-focussed, collaborative, factual and respectful (Wiggins, 2012) and focuses on knowledge, skills, practices and attitudes. ■ | A | Be sure to give proper, timely feedback. ■ | A | Do not be a problem solver for students but act like a resource: redirect and provide tips/hints. ■ | A - P | Ensure feedback serves as input for reflection and future actions.
	[D] Explicit teaching: students often solve problems intuitively by using their awareness and foreknowledge (Hennessy & McCormick, 1994; Roth, 1995). Students rarely solve problems in a strategic way by using (scientific) domain-related knowledge (Parkinson, 2001). Also new insights are rarely linked to underlying concepts. All of this results in trial-and-error behaviour (Popovic, 2004). To prevent this, teachers should help students making strategic decisions and knowledge domain connections (Kolodner, Gray, et al., 2003; McCormick, 1997). By doing this, processes and contents become explicit (Hennessy & McCormick, 1994). ■ | P | Discuss all learning objectives explicitly. ■ | A | Stimulate students to think out loud. ■ | A - P | Use moments of feedback and reflection as explication tools. ■ | A - P | Explicate extensive and complex elements in smaller units. ■ | A | Conscientiously use, connect and repeat proper (scientific) terminologies and insights emerging from the task.
Student to content interaction	**[E] Process-related issues**: First, mistakes are an important learning source and provide information about students' (pre)conceptions: mistakes must not be corrected prematurely, but should be provided by feedback (Kolodner, Gray, et al., 2003). Second, experiencing different contexts in which the same concepts occur enhances learning, because students' knowledge is always context-related and not directly related to decontextualized knowledge domains. Thus, de- and recontextualisation complemented by explication supports understanding (Brandsford et al., 2003; Fortus et al., 2004; Johnson, 1997; Parkinson, 2001). Third, time pressure impedes learning because students do not take ownership of the learning process (Murphy & Hennessy, 2001). Encouraging students using constructive feedback is to be preferred. Fourth, to incentivise the learning process sufficient control of the classroom management is needed through clear instructions and high-quality learning materials (Bruinsma, 2003). ■ | A | Do not correct mistakes prematurely but provide them with feedback. ■ | P | Make sure students experience multiple contexts in which the same concepts occur. ■ | A | Prevent time pressure: use constructive feedback to encourage students. ■ | A - P | Take care of clear instructions and (high-quality) learning materials and encourage students to use them.

Note. Partially adapted from Van Breukelen et al. (2016)

Data collection

To get informed about students' change in conceptual understanding an identical pre- and post-exam was used. A control group was used to determine a possible learning effect from completing the test. The multiple-choice questions were taken from the validated Determining and Interpreting Resistance Electric Circuit Test (DIRECT) specially designed for use with high school and university students (Engelhardt & Beichner, 2004). The test consisted of 46 items where each objective in Table 2 was served by multiple questions.

The participating principle investigators guided the challenge by using strategies in Table 4. To investigate the intensity of appealed strategies all activities were videotaped. Afterwards, the recordings were used to analyse teacher handling in detail and remarkable events, maybe important to complement the questionnaires and interviews, were noted. A questionnaire (open- and closed-ended) was used to study students' views on which teacher strategies were directive in reaching conceptual change or which guidance lacked. Questions were based on the STARR-method that provides a framework for reflection on learning outcomes (Verhagen, 2011). For deeper understanding of students' answers all students were included in retrospective semi-structured interviews where questionnaire items were leading. By combining questionnaire and interview data it is possible to identify which teacher strategies dominated science learning. Complemented by the intensity of applied strategies it becomes clear to what extent strategies were sufficiently addressed.

Analysis

The pre- and post-tests were scored per objective and for all questions by the percentage and number of correct answers. Percentages were used to calculate the gain index $\langle g \rangle$: ratio of actual average gain (%post-%pre) to the maximum possible average gain (100-%pre) (Hake, 1998). A Wilcoxon signed-rank test was used, because frequency analysis revealed a limited normal distribution, to investigate differences between pre- and post-scores. Calculating Cronbach's alpha established the internal consistency.

Video recording analysis was conducted by both principle investigators in order to establish an acceptable level of inter judgemental reliability. The investigators independently categorised and counted applied teacher interventions using (sub-)categories A till E in Table 4 including a short description. For this, the challenge was, based on Table 3, dived into four cohesive, nearly time-equal parts: stage 1-2 (introduction and exploration), stage 3 (investigation), stage 4-5 (designing) and stage 6-7 (construction and testing) and anticipatory skills had the most attention because preparatory issues were taken into account while constructing the design task. Afterwards the investigators compared their findings. Based on interventions categorised by both investigators the linear weighted Cohen's Kappa was calculated. After that, all inconsistencies were discussed and resolved and interventions not noticed by both investigators were discussed with in- or excluding as a result. Then, agreed interventions were rated by both investigators simultaneously by using a three point Likert scale (poor, fair, good) after which member checking was used to verify ratings. Finally, the results were translated into a teacher anticipatory intervention table.

For analysing questionnaire and interview data and combining it to other data, basically to get informed about the effectiveness of teaching strategies, elements of a grounded theory approach were used based on Charmaz (2006): a method for collecting and analysing qualitative data regarding actions in practice based on theoretical perspectives. For this, categories A till E (Table 4) served as sensitizing concepts and were used for initial coding of questionnaires (open-ended question) and transcripted interviews. Coding took place by the investigators concurrently in order to guaranty reliability, but also to record lines of thought and moments of decision-making; according to Charmaz (2006) important for increasing rationality and validity. By deepening the coded data sub-categories of common content were distracted where skills in Table 4 offered guidance. By doing this, theoretical sampling took place and more insight was offered into the coherence and interplay of teaching strategies included in the theoretical framework. Finally, it was possible to draw conclusions from available data and underlying theories.

Results

Pre- and post-test results

Table 5 shows how well students performed on each of the scientific objectives mentioned in Table 2. A Cronbach's alpha of 0.74 indicates the questions have sufficient internal consistency. The control group, used to determine a learning effect from completing the test, shows no average gain. For the experimental group the Wilcoxon signed-rank test indicates the overall gain is significant, $p<0.001$. Even though a significant progress is found, substantially more gain could be possible because the overall gain is just "medium" for each objective (Hake, 1998). Compared to gains found in several previous physics course studies, including LBD, this gain is comparable or slightly higher (Churukian, 2002; Coletta & Phillips, 2005; Kolodner, 2002b). Nevertheless, this gain pointed out to be sufficient for design realisation because both design groups delivered a successful design. The successfulness of the designs was determined by both investigators and concerned all design specifications A-C in Table 1.

Table 5

Results pre- and post-exam: experimental group (N=6) and control group (N=6)

Objectives and number of quest.		**Pre-exam**				**Post-exam**				**Difference**				
		Score		Perc.		Score		Perc.		Abs.		GainInd.[1]		Gain[2]
Object.	Number	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.	Cont.	Exp.
1	18	77	68	71%	63%	90	70	83%	65%	13	2	0.42	0.05	Medium
2	8	28	31	58%	65%	37	31	77%	65%	9	0	0.45	0.00	Medium
3	8	26	33	54%	69%	37	34	77%	71%	11	1	0.50	0.07	Medium
4	12	39	44	54%	61%	56	42	78%	58%	17	-2	0.52	-0.05	Medium
	Total	170	176	62%	64%	220	177	80%	64%	50	1	0.47	0.01	Medium

[1] Gain-index: $\langle g \rangle$ = (%post-%pre)/(100-%pre)

[2] High gain: $\langle g \rangle \geq 0.70$, Medium gain: $0.70 > \langle g \rangle \geq 0.30$, Low gain: $\langle g \rangle < 0.30$ (Hake, 1998)

The gains found for the individual objectives are comparable. Analysing the number of questions with no/low gain and high gain, specified in Table 6, confirms this conclusion. These questions are spread across the objectives and determining the related key concepts per objective there is a high degree of similarity. Key concepts concerning the high gain questions were appealed strongly during the challenge and were crucial for succeeding. The no/low gain questions appealed to underlying concepts that were barely exposed during the challenge.

Table 6

Number of high gain and no/low gain questions per objective

	No/low gain[1]		**High gain**[2]	
Obj.	Numb.	Key concept	Numb.	Key concept
1	3	Conceptual nature of resistance	4	Circuit operation based on wiring and switching
2	2	Nature of electrical energy and energy dissipation	2	Energy and power calculations
3	2	Behaviour of current in an electrical component	2	Behaviour of (combined) current sources
4	3	Effect of voltage change on circuit operation	3	Applying Kirchhoff's loop rule

[1] Pre-test: a maximum of 2 good answers (among 6 students); post-test: a maximum of 3 good answers

[2] Pre-test: a maximum of 2 good answers; post-test: 5 or 6 good answers

Intensity of applied teaching strategies

152 and 172 interventions were categorised by the investigators respectively where 138 interventions were noticed by both investigators which is 87% of the finally agreed interventions. Based on these 138 interventions the linear weighted Kappa κ_w is 0.61 (lower limit = 0.50; upper limit = 0.72), so inter rater agreement can be specified as moderate or on the very margin of substantial. Discussing and resolving afterwards revealed a few important issues responsible for a lot of the inconsistencies. These issues mainly concerned the strong entanglement of teaching skills in Table 4 and, to a lesser extent, non-visible interventions where, during the challenge, just the guiding investigator was aware of. The latter was simply solved by discussing the interventions. The first issue was resolved by agreement how to categorise strongly intertwined interventions. The examples in Table 7 show that categorisation has to take place based on the factual message of the intervention and hence the direct visible response of the student(s) that follows.

Table 7
How to categorise strongly intertwined interventions?

Situation	**Teacher action**	**Category** [Table 4]	**Underpinning**
Student uses the wrong equation to calculate the equivalent resistance of a parallel circuit.	"Why you use that equation?"… …[no reaction]… "Please explain this to your group members"	Collaboration [A]: externalising ideas within design group	Despite the fact the question has a reflective nature and aims for explaining content, collaboration is stimulated and takes place.
A design group measures the voltage of a solar cell; combined current and voltage measurement is required.	Perceiving the situation without intervention… [design group asks for approval]…Teacher stimulates to move on.	Process-related [E]: no premature intervention in case of failure.	Although collaboration is stimulated the intervention aims for learning from failures.
Student asks how solar cells behave when connected in series.	"That is for you to find out. Please search the internet for an answer and explain us".	Process-related [E]: stimulate students to use resources.	Although the teacher hopes the student will be able to explain conceptual content, the use of resources is stimulated.

After reaching agreement 159 interventions were included in Table 8 that shows how interventions are spread across the stages and (sub-)categories. It shows that 65% of all interventions directly appealed to providing feedback and stimulating collaboration. To a much lesser extent students were directly stimulated to make doing and knowing explicit. Table 8 also shows how the investigators rated the interventions. Rating took place by consultation and the clarity and quality of the intervention were taken into account. For example, in case of feedback the quality was established by using the rules for constructive feedback: relevant, well-timed, goal-directed, etc. By member checking the ratings were verified. For this, 5 interventions per category (25 in total) were discussed in detail with the student teachers afterwards that resulted in a limited number of adjustments not affecting the overall picture. In general, Table 8 demonstrates that the quality of teacher intervention was more than fair where feedback interventions and explicit teaching strategies lag behind a little.

Table 8

Teacher Anticipatory Interventions (TAI)

Learning-related elements and interventions based on Table 4		Number of interventions					Quality of interventions			
		Stage 1-2	Stage 3	Stage 4-5	Stage 6-7	Total	Poor [-1]	Fair [0]	Good [+1]	Average
A	**Collaboration**	**9**	**16**	**16**	**6**	**47**	**2**	**12**	**33**	**0.66**
1	Stimulating collaboration by referring back to the group	6	8	8	3	25	0	3	22	0.88
2	Encourage students to externalise and review ideas (within design groups)	3	5	6	2	16	2	5	9	0.44
3	Encourage students to externalise and review ideas (between design groups)	0	2	1	1	4	0	2	2	0.50
4	Other (e.g. Mediation in case of friction within design groups)	0	1	1	0	2	0	2	0	0.00
B	**Reflection**	**2**	**3**	**6**	**4**	**15**	**1**	**3**	**11**	**0.67**
1	Asking reflective questions to students; stimulate reflective thinking	1	3	4	1	9	0	2	7	0.78
2	Stimulate students to use (previous) reflection outcomes move on	0	0	2	2	4	1	0	3	0.50
3	Other (e.g. Verifying the quality of self-reflection by students)	1	0	0	1	2	0	1	1	0.50
C	**Feedback**	**8**	**19**	**21**	**9**	**57**	**9**	**14**	**34**	**0.44**
1	Providing corrective feedback; expressing concerns (verbal, teacher-driven)	2	8	10	4	24	3	6	15	0.50
2	Providing positive feedback; expressing appreciation (verbal, teacher-driven)	3	5	5	2	15	0	3	12	0.80
3	Responding to student questions by giving feedback (verbal, student-driven)	2	3	4	1	10	1	4	5	0.40
4	Other (e.g. Non-verbal communication that alludes to providing feedback)	1	3	2	2	8	5	1	2	-0.38
D	**Explicit Teaching**	**3**	**11**	**6**	**3**	**23**	**5**	**8**	**10**	**0.22**
1	Stimulate students to explicate doing (process-related)	0	2	4	2	8	2	4	2	0.00
2	Explain conceptual content to students (teacher-driven)	1	5	1	0	7	1	1	5	0.57
3	Stimulate students to explicate conceptual content (content-related)	2	3	0	1	6	2	2	2	0.00
4	Other (e.g. Explicate extensive/complex proceedings in smaller units)	0	1	1	0	2	0	1	1	0.50
E	**Process-related Issues**	**3**	**6**	**7**	**1**	**17**	**0**	**5**	**12**	**0.71**
1	Stimulate students to use available resources (e.g. internet, materials, etc.)	3	3	4	0	10	0	2	8	0.80
2	No premature intervention in case of (impending) failures/mistakes	0	1	2	0	3	0	2	1	0.33
3	Applying a flexible time management (preventing time pressure)	0	0	1	0	1	0	0	1	1.00
4	Other (e.g. Departing from intended procedures)	0	2	0	1	3	0	1	2	0.67
		25	**55**	**56**	**23**	**159**	**17**	**42**	**100**	**0.52**

Effectiveness of applied teaching strategies

According to questionnaire and interview responds students experienced the highest learning gains according to two aspects. First, the behaviour of (combined) solar cells and, second, a strengthening and anchoring of foreknowledge learned during secondary education (e.g. electrical calculations and measurements, circuit creation and operation) mainly because they were crucial for facing the complex challenge. These experiences are in accordance with the analysis of high-gain questions in Table 6. But why did they learn?

The questionnaire contained a set of events that directly appeal to the teacher guidelines in Table 4. Each of the learning-related elements (A-E) was served by 5 events (25 in total) that were listed in no particular order. Students had to rate each event by using a five point Likert scale (very poor, poor, fair, good, very good) based on what degree the event was helpful to learn more about electricity. Table 9 shows the results sorted by category. Furthermore, analysing open-ended questionnaire items and interview responds resulted in a list of events, shown in Table 10 including the number of references made by students to the events, that were most helpful according to students to learn about electricity.

Table 9

Effectiveness of events based on close-ended questionnaire items

	To what degree did the events listed below help you learn more about electricity?					
Teacher-driven events	- -	-	o	+	++	N/A
A. Collaboration	**1**	**6**	**12**	**8**	**3**	**0**
■ You had to work together within design groups	0	1	2	2	1	0
■ You were encouraged to externalise ideas to other students	0	2	3	1	0	0
■ Working in groups was organised by a fixed structure	1	1	4	0	0	0
■ You (your design group) had to share information with other design groups	0	2	1	2	1	0
■ The possibility to learn from other students	0	0	2	3	1	0
B. Reflection	**1**	**7**	**10**	**5**	**0**	**7**
■ You were obligated to self-reflect at fixed moments	1	3	2	0	0	0
■ Verifying the benefits of your reflection	0	1	2	0	0	2
■ The teacher stimulated reflective thinking during the process	0	2	2	2	0	1
■ You were assisted during reflection by peers and the teacher	0	0	2	2	0	2
■ You were encouraged to base future handling on reflection	0	1	2	1	0	2
C. Feedback	**0**	**3**	**9**	**12**	**5**	**1**
■ You had to write down and use received feedback	0	3	2	1	0	0
■ The teacher provided you with feedback instead of solutions	0	0	3	2	1	0
■ There were fixed moments for providing and receiving feedback	0	0	2	2	2	0
■ You had to process received feedback in order to move forward	0	0	2	3	0	1
■ The teacher provided you with immediate feedback during the process	0	0	0	4	2	0
D. Explicit teaching	**0**	**2**	**9**	**11**	**7**	**1**
■ The teacher discussed all learning objectives explicitly	0	0	5	1	0	0
■ The moments the teacher explained content	0	0	1	1	4	0
■ You were stimulated use scientific terminology	0	2	1	3	0	0
■ The fact you had to explain your own knowing and doing	0	0	1	4	1	0
■ Electricity-related concepts that were constantly repeated during the task	0	0	1	2	2	1
E. Process-related issues	**2**	**4**	**8**	**8**	**8**	**0**
■ The instructions and guidance you received during the challenge	0	0	1	2	3	0
■ The fact you could learn from failures.	0	1	2	3	0	0
■ The presence of learning materials (e.g. ICT, materials for experiments, etc.)	0	0	1	1	4	0
■ The fact the challenge was dived into smaller steps (stages)	0	1	3	1	1	0
■ You had to keep up a design diary	2	2	1	1	0	0

Table 10

Events helpful to learn more about electricity based on interviews and open-ended questionnaire items

Why have you learned about electricity? [1]	Number of references
Moments when underlying science was made explicit (supported by) by the teacher	22
Conducting experiments and applying insights in the design	15
Teacher-guided class discussions for sharing information and insights among design groups	13
Teacher feedback regarding conceptual content and process (no direct explication of science)	11
Clear instructions and transparency of what to do and deliver	9
Learning from peers within design groups	8
Other (e.g. learning from failures, absence of time pressure, reflection)	5

[1] Descriptions are revised to make categorisation possible.

Combining Table 9 and 10 demonstrates that explicit teaching strategies, teacher feedback and process-related issues are highly appreciated by students to learn about electricity. Especially when interventions directly appeal to underlying science (e.g. explaining science, conducting experiments, sharing insights during class discussions) or when an ongoing learning process is stimulated (e.g. clear instructions, process feedback, equipment of the learning environment).

Analysing students' criticism, also based on open-ended questionnaire items and interview responds, resulted in a list of non-constructive or lacking elements (Table 11) that according to students were not helpful to learn about electricity of even impeded learning. According to this list students mainly asked for additional learning events helping them to explicate science and even to de- and recontextualise addressed science. For this, students proposed traditional teaching techniques like performing demonstrations, doing theoretical exercises/problems, explaining theoretical backgrounds and concept mapping. Furthermore, students hackled the amount of administration (extensive design diary) mainly because of the limited amount of administration that was necessary to learn or move on. For example, also explaining the moderate appreciation of reflection in Table 9, there was a lot of requested reflection but in too little occasions this reflection affected advancement directly. As a result reflection becomes disturbing and abortive.

Table 11

Non-constructive or lacking learning events based on interviews and open-ended questionnaire items

What events/interventions were not helpful or lacked to learn more about electricity? [1]	Number of references
Too few moments for explaining electricity concepts (in general)	16
Absence of (training) exercises to activate prior knowledge or deepen/anchor new knowledge	11
Too much administration (extensive design diary)	10
One-sided focus on solar cells-related issues / limited variety in contexts	8
A limited active use of obligated moments of reflection (and other design diary content)	6
Other (e.g. task duration and a lack of concentration, friction within the design group)	4

[1] Descriptions are revised to make categorisation possible.

Discussion and implications

Despite the fact this study concerns a limited number of participants it enabled the detailed exploration of the interplay of teacher handling and concept learning during LBD. According to Zainal (2007) studies like this are necessary to provide holistic and in-depth information about complex social contexts where large quantitative studies often remain on the surface.

The developed framework of (concept) learning-related teacher strategies in Table 4, that forms the theoretical basis of this study, appeared to be very useful to study the interplay of concept learning and teacher handling in detail. During analysis the clustered interventions pointed out to be complete and identifiable where preparatory skills are important to predict learning outcomes and set objectives. For example, by studying the pre-post-exam outcomes it became clear, just like the previous study showed (Van Breukelen et al., 2016), that high gain questions were appealed strongly during the challenge and were crucial for succeeding. Thus, detailed task analysis is very useful to predict (conceptual) learning outcomes and unravels task-driven concepts that are addressed directly: direct concepts. Additional less directive concepts (indirect concepts), complementing the scientific concept domain, should be addressed otherwise (teacher-driven). The more, because the understanding of loose concepts strengthens when important interrelationships between the majority of concepts within the knowledge domain are understood (Stoddart, Abrams, Gasper, & Canaday, 2010).

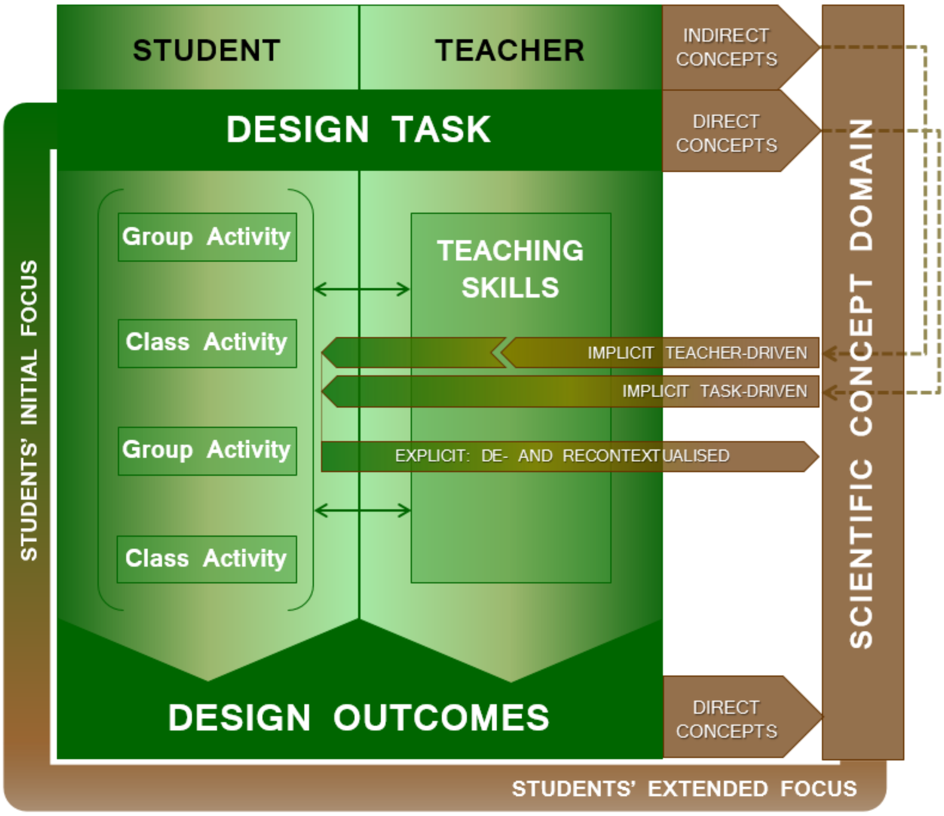
For learning concepts, explicit teaching strategies, teacher feedback and process-related issues were highly appreciated by students. Especially when those interventions directly appeal to underlying science (e.g. explaining science, conducting experiments, sharing insights during class discussions) or when an ongoing learning process was stimulated (e.g. clear instructions, process feedback, equipment of the learning environment). Unfortunately, Table 8 showed that most of the teacher interventions concerned the stimulation of collaboration and moments of feedback that were indirectly related to explaining science; like the third example in Table 7. Only 13 percent of all interventions concerned, to a greater or lesser extent, direct explication of underlying science. Furthermore, the challenge lacked sufficient de- and recontextualisation of addressed concepts that was also an important criticism expressed by students.

In general, the results of this study (and also the previous study) fit together with insights about knowledge transfer (Brandsford et al., 2003; Kolodner, Gray, et al., 2003; McCormick, 1997). To express this, the Design-based Science Interference Model in Figure 3 was developed. Conceptual knowledge students need to learn is always context-related (implicit) where direct concepts are strongly task-driven and indirect-concepts have to be teacher-driven and are (more or less) additional. To recognise and understand these concepts within the task context they have to become explicit. For this, the teacher is crucial as discussed before. To deepen conceptual understanding important interrelationships between concepts have to become clear: at first inside the task context and subsequently context-free. By addressing the concepts in new contexts (recontextualisation) further comprehension should take place. Doing this, the initial task-related student focus, that appeared to be very strong in the previous study (senior general education) compared to this study (student teachers), is extended to a better understanding of the entire (context-free) conceptual knowledge domain. Then, students should be able to master this conceptual framework independently of the context (knowledge transfer).

To strive for better knowledge transfer the LBD challenge concerning this study has several points of improvement from which every design-based science challenge can learn. First, more explicit teaching strategies should be used to explicate direct concepts. Second, indirect concepts have to be addressed (stronger) during the task including proper explication. Third, de- and recontextualisation of concepts is necessary for deeper understanding (e.g. by using traditional teaching techniques). Fourth, interrelationships between concepts should become explicit (e.g. through concept mapping). Further research will tell to what extent these suggestions enhance concept learning by LBD.

Figure 3

Design-based Science Interference Model



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