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Inquiry-based science education: scaffolding pupils' self-directed learning in open inquiry

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ABSTRACT

This paper describes a multiple case study on open inquiry-based learning in primary schools. During open inquiry, teachers often experience difficulties in balancing support and transferring responsibility to pupils' own learning. To facilitate teachers in guiding open inquiry, we developed hard and soft scaffolds. The hard scaffolds consisted of documents with explanations and/or exercises regarding difficult parts of the inquiry process. The soft scaffolds included explicit references to and additional explanations of the hard scaffolds. We investigated how teacher implementation of these scaffolds contributed to pupils' self-directed learning during open inquiry. Four classes of pupils, aged 10–11, were observed while they conducted an inquiry lesson module of about 10 lessons in their classrooms. Data were acquired via classroom observations, audio recordings, and interviews with teachers and pupils. The results show that after the introduction of the hard scaffolds by the teacher, pupils were able and willing to apply them to their investigations. Combining hard scaffolds with additional soft scaffolding promoted pupils' scientific understanding and contributed to a shared guidance of the inquiry process by the teacher and her pupils. Our results imply that the effective use of scaffolds is an important element to be included in teacher professionalisation.

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Introduction

This paper describes a multiple case study of four lesson modules on open inquiry in primary schools. We investigated how the implementation of hard and soft scaffolds within the inquiry process enabled teachers to facilitate their pupils' self-directed learning.

In Europe, different programmes centralise inquiry-based science education (IBSE) as a pedagogical approach to improve the understanding of scientific knowledge and promote a scientific attitude (e.g. Bolte & Rauch, 2014; Maaß, Reitz-Koncebovski, & Billy, 2013). IBSE addresses pupils' curiosity and enables them to formulate a research question about a scientific topic of their interest. Subsequently, pupils conduct their own investigation and draw conclusions in order to answer their research question. The role of the

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teacher is to facilitate pupils' inquiries (Lazonder & Harmsen, 2016; Van Uum, Verhoeff, & Peeters, 2016) by addressing conceptual understanding, inquiry procedures, and the way scientific knowledge is generated and communicated (Duschl, 2008; Furtak, Seidel, Iverson, & Briggs, 2012).

Unfortunately, primary school teachers often experience difficulties in determining how much guidance to provide to their pupils (Yoon, Joung, & Kim, 2012; Zion, Cohen, & Amir, 2007). They can either control the learning process, enable pupils to guide their own inquiries, or share the guidance of the learning process with their pupils. Teachers can, for example, control the learning process by providing research questions; pupils can guide their own learning by formulating their own research questions; and the teacher and pupils can share the guidance of the learning process when pupils adjust research questions provided by the teacher (National Research Council [NRC], 2000). In open IBSE, it is important for teachers to support pupils' progress in the different phases of inquiry (Van Graft & Kemmers, 2007), for example, by promoting the acquisition of conceptual or procedural knowledge (Van Uum et al., 2016). In addition, teachers should support pupils to direct their own inquiries. However, it is yet unclear how teachers can facilitate their pupils' inquiries while promoting their self-directed learning.

When guiding open inquiry, scaffolds can be used to increase pupils' understanding of the inquiry process (e.g. Saye & Brush, 2002; Simons & Klein, 2007). In education, a scaffold is a temporary support that is gradually faded when pupils are more and more able to achieve learning goals without the scaffold (Lajoie, 2005). It is important to provide scaffolding in pupils' 'zone of proximal development' (Vygotsky, 1978; Wood, Bruner, & Ross, 1976) by assisting them to comprehend components of a task which they cannot comprehend by themselves. Scaffolds can be divided into hard and soft scaffolds (Saye & Brush, 2002). Hard scaffolds are 'static supports that can be anticipated and planned in advance based on typical student difficulties with a task' (Saye & Brush, 2002, p. 81). In addition to hard scaffolds, 'soft scaffolds are dynamic and situational. Soft scaffolds require teachers to continuously diagnose the understandings of learners and to provide timely support based on student responses' (Saye & Brush, 2002, p. 82). When implementing scaffolds, it is important to diagnose pupils' prior knowledge and to provide support in their zone of proximal development. Finally, teacher support should fade and the learning process should be gradually handed over to the pupils (Smit, Eerde, & Bakker, 2013).

In this paper, we address how the implementation of hard and soft scaffolds facilitates pupils' self-directed learning. The scaffolds in this study are based on a pedagogical framework developed in a previous study (Van Uum et al., 2016). The framework distinguishes seven phases of inquiry: introduction, exploration, designing the investigation, conducting the investigation, conclusion, presentation/communication, and deepening/broadening (Van Graft & Kemmers, 2007). In each of these phases it proved important to address one or more domains of scientific knowledge: the conceptual domain (body of knowledge); the epistemic domain (knowledge about the nature of science and the generation of scientific knowledge); the social domain (research communication and collaboration); and the procedural domain (procedures, such as formulating a research question) (Van Uum et al., 2016). For example, in the exploration phase, addressing the conceptual domain implies retrieving pupils' prior knowledge and improving their understanding about concepts relevant to their inquiries. This enables pupils to formulate a research question in the subsequent phase of inquiry.

The pedagogical framework provides examples of interventions to support the inquiry process, but lacks tangible tools for pupils to use during their inquiries. In the current study, we developed tools or scaffolds for the combinations of inquiry phases and domains of scientific knowledge that required the most teacher support. We expect that these scaffolds enable pupils to proceed with the subsequent phases of inquiry and facilitate their self-directed learning. We investigated how teachers introduced the hard scaffolds as well as how they provided soft scaffolds that improved pupils' understanding of the inquiry process and enabled them to direct their own learning. The central question of the current study is: How does teacher implementation of hard and soft scaffolds contribute to pupils' self-directed learning during open inquiry?

Research design

To address our research question, we conducted a multiple case study of four lesson modules on open inquiry in three primary schools that were supported by Science Education Hub Radboud University. This Science Education Hub has extensive experience with inquiry activities for primary education and translates research of Radboud University into IBSE lesson modules in collaboration with researchers, pre-service and in-service primary school teachers, and teacher trainers. The inquiry-based pedagogical approach in these lesson modules is based on the seven phases model of Van Graft and Kemmers (2007). After six months of collaboratively developing an IBSE lesson module, primary school teachers implement it in their classrooms. Each lesson module contains about 10 lessons and each lesson lasts 1 to 1.5 hours.

Description of the four cases

The four teachers are all female and teach pupils (aged 10–11) in primary school. The teachers of cases 1, 2, and 3 participated in project teams that translated research studies into inquiry-based lesson modules facilitated by Science Education Hub Radboud University. The fourth teacher is a substitute teacher who did not participate in a project team and relied on an experienced IBSE colleague for ideas and activities. The four cases are discussed hereafter and the content of each classroom project is elaborated in the Appendix.

Case 1: The school is situated in a rural area. A classroom of 29 pupils and their two part-time teachers participated in the IBSE project on the theme of Higgs. Higgs was discovered in a particle accelerator in which protons collide. The concept of Higgs can explain why particles have mass. To conduct an investigation based on subthemes of Higgs, such as acceleration and weight, a group of pupils formulated the following research question: 'What falls faster: a marble or a tennis ball?' The teacher who had the leading role in the project is aged 46 and has 6 years of teaching experience. She has a Bachelor's degree in primary education and is studying for a Master's degree in education. She and her pupils have experience with a pedagogy resembling IBSE, but which only includes literature research.

Case 2: The school is situated in an urban area. A classroom of 21 pupils was engaged in the lesson module 'the world upside down' and explored different ways of looking at the world by people from different cultures, religions, generations, etc. Pupils in this case investigated, for example, whether adults or children were more willing to donate an amount of money to a charity. The teacher, aged 60, has 18 years of teaching experience and a Master's degree in adult education. She is familiar with demonstrating scientific experiments, but she and her pupils have no prior experience with IBSE.

Case 3: The school is the same school as in case 2 and the project topic is also 'the world upside down'. A classroom of 22 pupils was involved in the IBSE project. The pupils investigated, for example, the similarities and differences in opinions and viewpoints between Dutch people and refugees from Syria and Afghanistan. The teacher, aged 23, taught an IBSE project as a pre-service teacher in her second year of college, and is now in her final study year. The pupils conducted a smaller inquiry project in their previous school year.

Case 4: In this school, situated in an urban area, 29 pupils and their substitute teacher, aged 42, participated in the lesson module 'networks in the brain'. This topic refers to different brain areas, such as the visual, auditory, and motor cortex, which are interconnected. Pupils in this case investigated, for example, whether people could remember things better by hearing or by sight. The teacher recently started to work at the school and has 16 years of teaching experience. She has a Bachelor's degree in primary education. Neither she nor her pupils have any prior experience with IBSE.

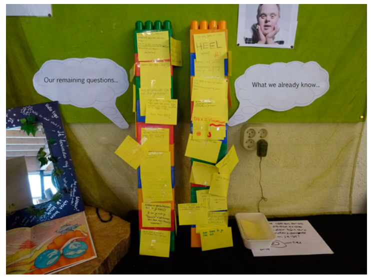
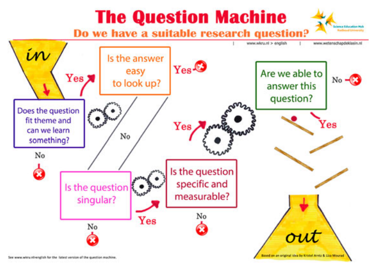
Intervention

Based on video-analyses of pupils' learning difficulties during several inquiry cycles, it proved important to focus on domains of scientific knowledge (conceptual, procedural, social, and epistemic) in the different phases of inquiry (Van Uum et al., 2016). Therefore, in the current study, we designed scaffolds for each inquiry phase. Each hard scaffold focused on an important combination of domain of scientific knowledge and phase of inquiry, based on our previous study.

We developed the hard scaffold 'poster with inquiry phases', aimed at understanding these phases, to promote pupils' epistemic knowledge in the introduction phase of inquiry. In the exploration phase, we used the 'question wall' to elicit initial questions by differentiating between acquired knowledge and remaining questions. We developed the 'question machine' to facilitate the formulation of research questions in the design phase of inquiry. To support the data collection during the actual inquiry, we used the scaffold 'recording data'. The scaffold 'difference between results, conclusion and discussion' was designed to understand these differences and to implement them in pupils' own investigations. We used the hard scaffold 'presenting an inquiry' to support pupils as they developed and gave research presentations. In the final phase of inquiry, we advised teachers to select scaffolds to reflect on pupils' investigations and further deepen and broaden their knowledge. An overview of these scaffolds, their contents, and goals is provided in Table 1. The latest versions of the scaffolds can be found on the website of Science Education Hub Radboud University (http://www.ru.nl/wetenschapsknooppunt/english/materials/).

We developed two soft scaffolds for teachers to use when their pupils asked questions or needed support, based on the model of soft scaffolding of Van de Pol, Volman, Oort, and Beishuizen (2014). As teachers need extensive professionalisation to implement the different steps of this model, we decided to focus on step 3, 'providing contingent support'. Since teachers are used to answering pupils' questions instead of promoting their self-

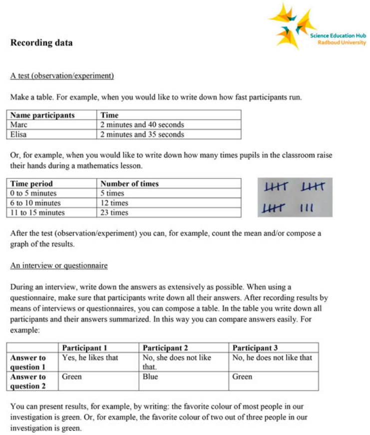
Table 1. Analytical framework.

Phase and domain	Content hard scaffold	Visual hard scaffold	The hard scaffold enables pupils to …	Self-direction visible as pupils …
1 Introduction: epistemic	Poster with inquiry phases: an inquiry cycle consisting of seven phases of the inquiry process.		… understand on which part of the inquiry cycle they are working. … understand that real researchers also use this cycle to conduct their investigations.	… discuss learning goals of the poster and plan learning activities. … mention the poster or elements of it to explain the phase of inquiry they are working on, and remark that they conduct their investigations the same way as real researchers. … use the poster to monitor or evaluate the inquiry process.
2 Exploration: conceptual	Question wall: consisting of a part with questions that pupils already answered during the exploration phase and a part with questions that remain to be answered. Clusters of the latter provide a base for pupils' research questions in the subsequent inquiry phase.		… formulate a question that fits the content of a cluster on the question wall, or fits the topic of the project when the questions are not clustered. … differentiate between acquired knowledge and remaining questions.	… discuss and plan the formulation of questions for the question wall. … formulate questions related to the theme or to subthemes of the classroom project. … regulate the learning process by evaluating whether questions fit the part 'what you already know' or the part 'what you still want to know' and attach questions to the question wall.
3 Designing the investigation: procedural	Question machine: the machine contains five criteria to improve a research question: does the question fit the theme of the classroom inquiry project and can we learn something; is the answer easy to look up; is the question singular; is the question specific and measurable; and are we able to answer this question?		… formulate a research question that meets the five criteria of the question machine.	… discuss and plan the formulation of research questions by means of the question machine. … formulate research questions that meet the criteria of the question machine. … mention elements of the question machine when monitoring and evaluating the formulation of research questions.

(*Continued*)

Table 1. Continued.

Phase and domain	Content hard scaffold	Visual hard scaffold	The hard scaffold enables pupils to …	Self-direction visible as pupils …
4 Conducting the investigation: procedural	Recording data: a document with explanations of how to record data when conducting an investigation. The document advises to compose a table in which the score or opinion of each participant or test result is recorded.	See reproduced document below	… record data in an organised way.	… discuss and plan how to record data in an organised way. … write down their test results in an organised way, e.g. by using tables to record data in which they differentiate between participants and test results. … monitor and evaluate the recording of data.
5 Conclusion: procedural and epistemic	Difference between results, conclusion and discussion: the document advises pupils to present their results in a graph or chart and write down the most important results. Furthermore, the document explains that when drawing a conclusion, the results are connected to the research question to answer this question. Finally, the discussion is explained by asking pupils to think about why they found these results and how the results match their previous expectations.	See reproduced document below	… process their results in graphs, tables or figures, draw a conclusion to answer their research question, and reflect on their results.	… plan to process results, draw a conclusion and evaluate the research process. … calculate a mean score or percentages, compose graphs, tables or figures, etc. to process results. … monitor the processing of results and evaluate the results by drawing a conclusion and reflecting on the results.



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Recording data

A test (observation/experiment)

Make a table. For example, when you would like to write down how fast participants run.

Name participants	Time
Marc	2 minutes and 40 seconds
Elisa	2 minutes and 35 seconds

Or, for example, when you would like to write down how many times pupils in the classroom raise their hands during a mathematics lesson.

Time period	Number of times
0 to 5 minutes	5 times
6 to 10 minutes	12 times
11 to 15 minutes	23 times

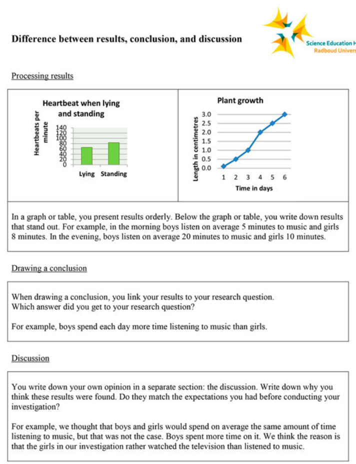
After the test (observation/experiment) you can, for example, count the mean and/or compose a graph of the results.

An interview or questionnaire

During an interview, write down the answers as extensively as possible. When using a questionnaire, make sure that participants write down all their answers. After recording results by means of interviews or questionnaires, you can compose a table. In the table you write down all participants and their answers summarized. In this way you can compare answers easily. For example:

	Participant 1	Participant 2	Participant 3
Answer to question 1	Yes, he likes that	No, she does not like that.	No, he does not like that
Answer to question 2	Green	Blue	Green

You can present results, for example, by writing: the favorite colour of most people in our investigation is green. Or, for example, the favorite colour of two out of three people in our investigation is green.



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Difference between results, conclusion, and discussion

Processing results

In a graph or table, you present results orderly. Below the graph or table, you write down results that stand out. For example, in the morning boys listen on average 5 minutes to music and girls 8 minutes. In the evening, boys listen on average 20 minutes to music and girls 10 minutes.

Drawing a conclusion

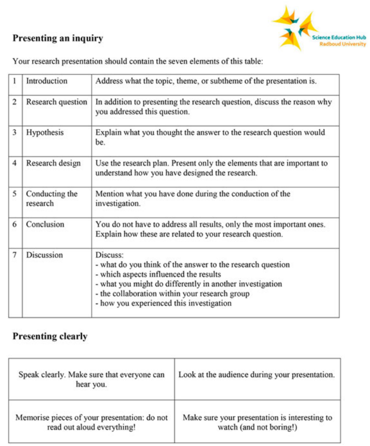
When drawing a conclusion, you link your results to your research question. Which answer did you get to your research question?

For example, boys spend each day more time listening to music than girls.

Discussion

You write down your own opinion in a separate section: the discussion. Write down why you think these results were found. Do they match the expectations you had before conducting your investigation?

For example, we thought that boys and girls would spend on average the same amount of time listening to music, but that was not the case. Boys spent more time on it. We think the reason is that the girls in our investigation rather watched the television than listened to music.

6 Presentation/ communication: social	Presenting an inquiry: a document containing: (1) an overview of parts of the inquiry process, such as the research question and hypothesis, combined with actions. For example, 'Discussion: Explain what you think of the answer to the research question, the influences on the results, things you might change in a future investigation, how you collaborated within your research group, and your opinions regarding your investigation'. (2) suggestions when presenting the research, such as 'Look at the audience' and 'Do not read out aloud your sheets'.		… include the different elements of their investigation in their research presentation and present the research clearly.	… prepare and plan to develop a research presentation. … develop the presentation or present the research and include elements of the hard scaffold. … monitor and evaluate (the process of composing) the research presentation.
7 Deepening/ broadening: all domains or specific choices	Reflection and further deepening and broadening of knowledge and skills via all previous scaffolds.	For example, using the poster with inquiry cycle of Science Education Hub Radboud University to reflect on the generation of scientific knowledge.	… elaborate their knowledge and skills via all previous scaffolds.	… determine which parts of the inquiry process need to be elaborated further. … mention (elements of) one or more scaffolds during the elaboration of their knowledge after the presentation phase of inquiry. … monitor and evaluate the elaboration of knowledge.

Presenting an inquiry

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Your research presentation should contain the seven elements of this table:

1	Introduction	Address what the topic, theme, or subtheme of the presentation is.
2	Research question	In addition to presenting the research question, discuss the reason why you addressed this question.
3	Hypothesis	Explain what you thought the answer to the research question would be.
4	Research design	Use the research plan. Present only the elements that are important to understand how you have designed the research.
5	Conducting the research	Mention what you have done during the conduction of the investigation.
6	Conclusion	You do not have to address all results, only the most important ones. Explain how these are related to your research question.
7	Discussion	Discuss: - what do you think of the answer to the research question - which aspects influenced the results - what you might do differently in another investigation - the collaboration within your research group - how you experienced this investigation

Presenting clearly

Speak clearly. Make sure that everyone can hear you.	Look at the audience during your presentation.
Memorise pieces of your presentation: do not read out aloud everything!	Make sure your presentation is interesting to watch (and not boring!)

directed learning, we chose soft scaffolds that we expected to be easy to implement: (1) refer to a hard scaffold, and (2) provide examples or explanations regarding the hard scaffold.

As part of project teams, the teachers of cases 1, 2, and 3 had translated research into inquiry-based lesson modules and had gained knowledge about inquiry-based learning. The fourth teacher was informed about inquiry-based learning by a colleague. To be able to use the scaffolds in their teaching practice, we instructed the four teachers individually (cases 1 and 4) or together (cases 2 and 3) for about 1.5 to 2 hours. During our instruction, we introduced the domains of scientific knowledge and clarified their connection to the different phases of inquiry (Van Uum et al., 2016). Furthermore, we explained the scaffolds and discussed the learning goals regarding the domains of scientific knowledge to address in each phase of inquiry (see Table 1). We asked the teachers to implement each scaffold when and how they considered it most appropriate. Therefore, teachers could choose to introduce a scaffold comprehensively or, for example, hand out the scaffold to pupils to discuss in their research groups. Furthermore, we asked the teachers to gradually hand over the responsibility for the learning process by providing soft scaffolds to stimulate pupils' use of the hard scaffolds and to enable them to solve their own problems within the inquiry process.

Data collection

Each teacher carried a voice recorder to capture her instructions and discussions with pupils, and to establish whether or not she used hard and soft scaffolds to support her pupils. Additionally, each lesson was observed, notes were taken, and a second voice recorder was used to capture pupils' inquiry process and their use of hard and soft scaffolds. The teachers were interviewed after each lesson and after the entire project about their experiences in implementing the scaffolds. After finishing the lesson module, about half of the pupils were interviewed in their research groups: 15 pupils of case 1; 12 pupils of case 2; 10 pupils of case 3; and 11 pupils of case 4. The interviewed pupils of case 1 were divided into seven research groups of two pupils each, and the interviewed pupils in cases 2, 3, and 4 were each divided into three research groups of about four pupils each. These pupils were asked about the teachers' instruction and the support by means of hard and soft scaffolds. The video and audio data were triangulated with the interview data to determine how the teachers implemented the hard and soft scaffolds, and how their pupils used these during their inquiry process.

Analysis

Data analysis focused on whether and how the hard and soft scaffolds were implemented and contributed to pupils' understanding of the inquiry process and their self-directed learning. To determine teacher implementation of the scaffolds, we selected all audio fragments with reference to specific hard scaffolds or activities linked to these scaffolds for each phase of inquiry (see Table 1). For each fragment, we determined whether the specific scaffold was discussed during the preparation of, engagement in, and regulation of learning activities (Boekaerts & Simons, 1995; Shuell, 1988). Fragments were labelled as 'preparation' when prior knowledge was retrieved, learning goals were chosen and learning activities were planned. The label 'engagement' was used for fragments in which learning activities, such as understanding, integration, and application of knowledge, were conducted, and 'regulation' referred to monitoring or evaluating the learning process. In addition to the implementation of hard scaffolds, we recorded whether and how the teachers and pupils used soft scaffolds (Smit et al., 2013; Van de Pol et al., 2014) by (1) referring to a hard scaffold, and (2) providing examples or explanations regarding the hard scaffold.

The scaffolds focused on the domains of scientific knowledge (conceptual, epistemic, social, and procedural) to guide pupils through each phase of inquiry. We determined whether pupils developed scientific understanding and used the scaffolds within their investigations. In the interviews after the lesson modules, we asked them to explain their understandings of and actions within each phase of inquiry. The scaffold 'question machine', for example, focused on the formulation of a research question (procedural domain) in the design phase of inquiry. In the interview, we asked pupils to mention the criteria of a good research question, and the research question they formulated as part of their inquiry. In addition, we analysed the content of each selected audio fragment to find evidence for pupils' (lack of) understanding of the specific domain of scientific knowledge that was centralised in each phase of inquiry. We established, for example, whether pupils' presentations of their investigations matched the content of a research presentation on the hard scaffold 'presenting an inquiry'.

The amount of self-directed learning during open inquiry was determined by labelling each fragment as 'teacher guided', 'pupil guided', or 'guided by both teacher and pupil(s)' (NRC, 2000). We labelled a fragment as 'teacher guided' when the teacher led the conversation and asked questions, and the pupils followed her directions. A fragment was labelled as 'pupil guided' when pupils asked questions and/or provided information, and the teacher followed the pupils' discussion without presenting information herself. In addition, pupils' discussions about a scaffold or its goals were labelled as 'pupil guided'. The label 'both teacher and pupil guided' applied when both parties guided the conversation, e.g. by asking and answering questions.

Finally, we selected all interview fragments that contained references to the hard and soft scaffolds and combined these with the audio fragments to determine whether our observations matched the teachers' and pupils' opinions and understanding of the scaffolds.

Results

In the subsequent paragraphs, we provide a thick description of the implementation of the scaffolds, and the gradual handover of the learning process to pupils based on our audio and interview analyses of all four cases. Relevant differences between the cases are highlighted and illustrated with examples. In addition to this qualitative account of the learning process in each phase of inquiry, an overview is provided of the evidence regarding pupils' elaborated understanding of the inquiry process (see Table 2).

Phase 1: introduction

The seven phases of a scientific inquiry were introduced as a preparation for pupils' own investigations. The teacher of case 3 asked pupils about their prior knowledge of the inquiry process, since her pupils conducted an investigation in the previous school year. Each teacher discussed the phases of inquiry in chronological order while pupils observed

Table 2. Evidence of pupils' elaborated understanding of the inquiry process.

			Evidence based on 16 interviewed groups of pupils	
Inquiry phase	Pupils' learning goals focused on …	Classroom observations showed that …	Pupils' products	In the final interviews …
1	… understanding the inquiry cycle, informed by the scaffold 'poster with inquiry phases'.	… pupils hardly mentioned the inquiry phases during their investigations.	Pupils did not develop a product.	… 8 groups were able to mention one or more inquiry phases without the poster: - 1 phase: 2 groups - 2 phases: 2 groups - 4 phases: 2 groups - 5 phases: 1 group - 6 phases: 1 group
2	… formulating questions that fit the (sub)theme(s) of the scaffold 'question wall'.	… pupils formulated questions related to the (sub)theme(s) of their inquiry project.	The formulated questions by all of the 16 groups of pupils matched the theme or subtheme of the classroom inquiry project.	… pupils did not refer to the question wall as a useful tool.
3	… formulating a research question that meets the five criteria of the scaffold 'question machine'.	… pupils were able to reformulate questions into research questions, meeting the criteria of the question machine.	- 6 groups had formulated questions that met 4 criteria of the question machine. - 8 groups had formulated questions that met 3 criteria. - 1 group had formulated a question that met 1 criterion.	… 13 groups of pupils mentioned the question machine as one of the most useful scaffolds in their inquiry process. … when asked how to formulate a research question, - 6 groups mentioned criteria of the question machine. - 4 groups referred to other criteria, such as 'the question is not answered with yes or no'. - 6 groups were unable to name any criteria.

4	… recording data in an organized way, informed by the scaffold 'recording data'.	… pupils reminded each other to write down their data in an organised way.	- 11 groups recorded their data by differentiating between participants or tests. - 3 groups recorded data, such as 25.7 seconds, without referring to a participant or test. - 1 group decided to remember their results. - 1 group had difficulty writing down opinions of participants while interviewing them.	… the 15 groups that had recorded their data, were able to describe how they had written down the data they collected.
5	… processing results in graphs, tables or figures, drawing a conclusion, and reflecting on their results, using the scaffold 'difference between results, conclusion and discussion'.	… pupils developed graphs and tables, answered their research questions and provided recommendations for future research.	- 13 groups had calculated a mean, had written a summary about their results, or had composed tables and/or graphs. - 3 groups had only written down their data without further processing.	- 7 groups were able to provide a conclusion. - 5 groups did not understand the word 'conclusion', but were able to answer their research question when asked. - 4 groups were unable to provide a conclusion. - all 16 groups mentioned recommendations for future inquiries.
6	… presenting the research by means of the scaffold 'presenting an inquiry'.	… pupils included elements of the scaffold 'presenting an inquiry' in their presentations, such as designing and conducting the investigation.	- 7 out of 15 groups included all elements of the scaffold 'presenting an inquiry' in their presentation, although 3 groups put them in a different order. - 5 groups forgot to mention one element of the scaffold. - 3 groups forgot to include two elements of the scaffold.	… 8 groups of pupils specifically mentioned the scaffold 'presenting an inquiry' as one of the most useful within their inquiry project.

the hard scaffold ‘poster with inquiry phases’. The teacher of case 2 made connections to real research by explaining that pupils were going to participate in a project that was connected to a real scientific investigation of the university. All four teachers explained learning goals and pupils’ activities in each phase of inquiry, as illustrated by the case 2 teacher:

Teacher: In groups you will pass through the circuit [of activities related to the project theme ‘the world upside down’]. Also to let you think about what you would like to know. You cannot just formulate any [research] question. Your question needs to be connected to the project of the university. (…) Exploration is: what would you like to know.

Neither teachers nor pupils referred explicitly to the poster after its introduction. Therefore, the amount of self-directed learning could not be determined, as pupils did not engage with the poster nor regulated their learning by means of the poster.

The poster contributed to pupils’ insight into the inquiry process. However, as they did not internalise the inquiry phases, they would need the visualisation of the inquiry process on the poster again to guide their future inquiries. It is expected that after several investigations, pupils would gradually be able to proceed independently to each subsequent inquiry phase.

Phase 2: exploration

The goal of this inquiry phase was to explore the theme of the inquiry project and to formulate initial questions as a starting point for research questions in the subsequent phase of inquiry. To stimulate knowledge acquisition and evoke questions on subthemes, each teacher showed videos and provided activities for her pupils, such as a game in which key concepts were clarified, and/or a plenary discussion in which these concepts were connected to everyday contexts. Subsequently, each teacher introduced the hard scaffold ‘question wall’ by reminding pupils of the subthemes of the classroom inquiry project and asking them to formulate initial questions about these subthemes. Pupils engaged with the question wall by formulating and writing down questions, and attaching them to one of the subthemes on the question wall, or writing them on a piece of paper that distinguished between these subthemes, as is illustrated by the following quote of case 1:

Pupil: Teacher, I have the question: ‘Is there also Higgs inside people?’ But how do I write that down?

Teacher: [To the entire classroom] There are some questions that do not fit one of the three categories [the subthemes on the question wall]. But they can be very good questions. Research questions. Write them down, but write them, for example, in the left corner [of the piece of paper].

However, the teachers noticed that the formulated questions would be difficult to investigate by pupils. The teacher of case 2 (theme: ‘the world upside down’) explained in the interview after the lesson about the question wall:

Teacher: There appeared many questions as: ‘What if there would be no electricity’, ‘What if there would be no people’, ‘What if people were not able to talk’, and ‘What if there were no colours’.

To evoke questions that could be investigated by pupils, the teacher of case 1 provided additional explanations of difficult concepts related to subthemes within the lesson module. The case 2 teacher reminded her pupils of the activities they had conducted during the exploration phase and stimulated them to formulate a question related to one of these activities. Subsequently, the pupils formulated questions supported by their teacher.

Together, the pupils and their teacher evaluated whether these questions matched the project subthemes and whether they could be investigated by pupils.

The teachers hardly used soft scaffolds to refer to the question wall in the subsequent phases of inquiry. A possible explanation is that pupils were asked to take the questions and reformulate them into research questions to guide their investigations. As a result, the question wall was no longer visible as a hard scaffold to look back on.

In short, the question wall functioned as a useful tool to stimulate the formulation of initial questions. After the teacher had prepared the learning process by introducing the question wall, the pupils engaged with this hard scaffold. They were able to formulate initial questions that matched the theme of the project, but needed their teachers' support to formulate and evaluate questions that could be investigated within the classroom project.

Phase 3: designing the investigation

In this inquiry phase, pupils were asked to reformulate their initial questions into research questions and to design their investigations. To prepare the reformulation of questions, the teachers explained the criteria of a good research question on the hard scaffold 'question machine'. They asked their pupils to judge and improve example questions to promote understanding of these criteria, as the following quote of case 2 illustrates.

Pupil 1: Is the question singular?
Pupil 2: No?
Pupil 1: Yes, it is singular. Is it specific and measurable? You don't know what that means, right?
Pupil 2: No.
Pupil 1: I don't know what that means either.
Teacher: Ok, specific. Let's say, you want to know how quick vegetables decay. You can do that, but what is the problem with that question? What do you choose?
Pupil 1: Yes, what kind of vegetable.
Teacher: What kind of vegetable, exactly. Therefore, it is not specific enough.

Subsequently, the teachers stimulated pupils to engage with the question machine and to reformulate their own initial questions. The teachers reminded pupils to use the question machine and provided additional explanations of the criteria on the question machine. In addition, in case 3, the pupils reminded the teacher of the question machine, as is illustrated in the following quote.

Pupil: Can we have the question machine on the digital board, so we can revise it [their research question]?
Teacher: It is good that you ask me that. I am going to arrange it for you immediately.

Pupils were able to apply the criteria of the question machine and to formulate and evaluate questions as the following quote of case 2 (theme: 'the world upside down') illustrates:

Teacher: Subject: living without digital media. What is the research question? What do you want to know?
Pupil: How difficult it is, whether it is possible to live without it, will you be happier.
Teacher: You can write that down here.
Pupil: But [name teacher], then the question will not pass through the question machine? Because, it is not a single question.
Teacher: Then it will no longer be singular. Well observed! Then you can limit yourself to: is it possible to live without it, or is it difficult.
Pupil: Is it possible.
Teacher: Can six pupils of year 6 live without digital media for five days? Well observed [name pupil]. Write that down here.

The example shows that the pupil evaluated the formulated question and concluded that it was not a singular question. Although the engagement with the question machine and the evaluation of research questions were mostly directed by both the teacher and her pupils, the example illustrates that teachers might need additional support in order to work with the question machine. This was confirmed by the teachers of cases 1, 2, and 4. They indicated in the interviews to require a deeper understanding of the formulation of research questions.

In the four cases, both the pupils and their teachers valued the question machine as a useful scaffold to support the formulation of a research question. After the teacher had prepared the formulation of questions, most pupils were able to formulate a research question and evaluate its quality in collaboration with their teacher.

Phase 4: conducting the investigation

The goal of this phase was to collect data in an organised way, supported by the hard scaffold 'recording data' (see Table 1). Each teacher prepared the data recording by introducing the scaffold either to the entire class (cases 1, 2, and 4) or within pupils' research groups (case 3). The teachers explained that pupils should not mix the results of participants or tests when conducting their investigations, as that would cause difficulties during data analysis. Subsequently, each teacher prepared the data recording together with her pupils by connecting the content on the scaffold to pupils' own inquiries. For example, by drawing a table and asking pupils how to categorise results within the table.

When collecting data, pupils engaged with the tables they had drawn for this purpose. Both teachers and pupils regulated this part of the inquiry process by reminding (other) pupils to record data. The following quote of case 1 shows that a pupil reminded another pupil to write down their data.

Pupil 1: There the paper is and I will tell the time. I will shout it to you. Ok, three, two, one [the pupil drops a marble from a balcony on the top floor of the school]. Ok, you have to write down … do you have the pencil?
Pupil 2: A pen.
Pupil 1: At the big marble [the category 'big marbles' on their piece of paper] 0.94 [seconds].

However, classroom observations showed that five groups of pupils did not record data orderly, for example, because they recorded measurements, such as 25.7 seconds, without referring to a participant or test. In these groups, a soft scaffold by their teacher would have reminded pupils to apply the hard scaffold to their data recording.

To summarise, the hard scaffold 'recording data' was useful to understand how to record results. Most groups of pupils were able to record their data. After introducing the hard scaffold, the teacher directed the preparation of the data recording together with her pupils by connecting the hard scaffold 'recording data' to pupils' own inquiries. The pupils were engaged with the collection of data and both the teacher and her pupils regulated the data recording.

Phase 5: conclusion

In the conclusion phase, pupils were asked to process their results, draw conclusions, and evaluate their investigations supported by the hard scaffold 'difference between results, conclusion and discussion' (see Table 1). The teachers of cases 1, 2, and 3 introduced the hard scaffold in a plenary discussion, in case 3 followed by group discussions in each research group. Subsequently, the teachers stimulated the pupils in these three cases to prepare and plan the processing and evaluation of results. For example, by asking how pupils would write down and compare their results. The case 4 teacher did not explain the scaffold in a plenary meeting, but asked the head of each research group to discuss the scaffold with his or her group members.

The teachers of cases 1 and 2 and their pupils engaged with the hard scaffold and shared its application to pupils' investigations as they discussed together how to, for example, compose a graph or calculate a mean, as the following quote of case 1 illustrates.

Pupil 1: Can you help us? We have to count the mean of these seconds.
Teacher: Ok, the mean, this is how you do that. You count everything …
Pupil 2: Together. We already have started with that. And then divide it by 1, 2, 3 … 5. Right?
Teacher: Right, divide it by 1, 2, 3, 5. Yes. And then you have counted the mean.

In contrast, the teachers of cases 3 and 4 asked pupils to apply the hard scaffold to their own inquiries without additional teacher support. After the processing of results, each teacher (except for case 4) repeated the explanation of a conclusion and discussion to support pupils to answer their research question and evaluate their investigations. Subsequently, both the pupils and their teacher reflected on the results and answered pupils' research questions together. In addition, the teacher and her pupils shared the evaluation of pupils' inquiries.

Although the teachers of the other cases almost never used soft scaffolds to refer to the hard scaffold after its introduction, the teacher of case 1 reminded her pupils to write down their opinion about their investigation by referring to the hard scaffold 'difference between results, conclusion and discussion'.

In conclusion, after an introduction of the hard scaffold by the teachers (except case 4), pupils engaged with the scaffold and processed their results together with their teachers (cases 1 and 2) or on their own (cases 3 and 4). Most pupils were able to answer their research question and evaluate their inquiries in collaboration with their teacher.

Phase 6: presentation/communication

Pupils were asked to communicate their inquiries to an audience, such as their classmates and/or parents. The hard scaffold 'presenting an inquiry' stimulated pupils to include the different steps of their investigation in a research presentation, and to present the research clearly. As both the teachers and their pupils claimed that pupils were already able to present clearly (by speaking articulately, making the presentation interesting to watch, etc.), only the part of the scaffold that focused on including the different steps of the investigation in pupils' presentations will be discussed here.

To prepare pupils for their research presentations, the teachers of cases 1, 2, and 3 provided a whole-class introduction of the hard scaffold. They explained the elements of pupils' investigations that were to be included in their presentations, such as the research question, hypothesis, and conclusion. In contrast, the case 4 teacher handed the scaffold to each group of pupils to read and use themselves. Subsequently, in each case, pupils engaged with the hard scaffold and applied its content to their research presentations. In the following quote, pupils of case 4 explained to an observer how they developed their presentation.

Pupil: Designing the investigation. We wanted to do something with boys and girls. Who can do it [playing soccer] better. (…) So we thought, let's focus on a soccer movement.
Observer: Yes.
Pupil: This one is not that difficult. And the next one, I still have to do. That is conducting the investigation.
Observer: So, you are just following those steps on the paper [the hard scaffold 'presenting an inquiry'].
Pupil: Yes.

In addition, pupils were supported by their teacher who added elements to the presentation or reformulated phrases to make the presentation more comprehensible.

Soft scaffolds were used by both teachers and pupils during this inquiry phase to remind (other) pupils to use the hard scaffold, and to provide additional explanations when necessary. The teachers of the four cases valued the scaffold as it enabled pupils to independently criticise and improve their own presentations. In addition, it supported each teacher to evaluate (the development of) pupils' presentations.

In short, the scaffold 'presenting an inquiry' supported pupils to compose a research presentation in which important elements of their investigations were included. After the teachers had prepared the learning process by introducing the hard scaffold, both the teachers and their pupils guided the development and evaluation of the research presentations by applying the hard scaffold to pupils' investigations.

Phase 7: elaboration (deepening/broadening phase)

The goal of the elaboration phase was to broaden and deepen pupils' knowledge. For example, by clarifying challenging parts of the inquiry process. The teachers of cases 1 and 4 chose to end the inquiry project at the presentation phase as they needed to address other subjects in the curriculum. Although the teachers of cases 2 and 3 mentioned the duration of the lesson module as a disadvantage, they included a visit to the university to enable communication between pupils and real scientists. As the teachers did not use hard and soft scaffolds in this inquiry phase, the influence of the scaffolds on pupils' scientific knowledge and their self-directed learning cannot be determined.

General opinions on the inquiry module

After finishing the inquiry projects, the 4 teachers and 16 groups of pupils (about half of the pupils in each case) were interviewed about their general opinions on the lesson modules. In 14 groups, pupils were predominantly enthusiastic about their lesson module, while in 2 groups pupils had mixed opinions. Some elements of the lesson module were perceived to be difficult (mentioned in five groups), such as planning and drawing a conclusion. Other elements were not that interesting (mentioned in four groups), such as writing and working on the computer. Six groups specifically perceived the hard scaffolds to be useful to guide their investigations. In seven groups, pupils explained that the lesson module was instructive, as they had learned to investigate, work together, and improve their understanding of the theme of the lesson module.

Pupils in eight groups mentioned they appreciated the amount of self-directed learning during the inquiry project as they claimed to be capable of guiding their own inquiries. According to these pupils, they only needed their teacher to explain difficult topics and to provide examples, tips, and advice when necessary. Two groups had preferred extra explanations during their inquiries. The remaining six groups mentioned that they valued the teacher guidance because the teacher explained the inquiry project well. She answered questions directly, provided tips, and guided pupils to answer their own questions.

In the interviews, the teachers explained that pupils were motivated to work on their investigations (cases 1, 3, and 4), learned practical skills (case 1), learned to ask questions and to conduct an investigation to answer their questions (case 2), and guided their own learning while being responsible for their investigations (cases 3 and 4). However, the case 4 teacher mentioned it was difficult to determine pupils' achievements.

The teachers of cases 1, 2, and 4 perceived their pupil guidance to be rather superficial, because they had to divide their attention between many groups. In contrast, the case 3 teacher explained she was able to provide comprehensive guidance by regularly asking each group of pupils to discuss their investigation with her. In this way, she could provide support and keep an overview of the pupils' investigations.

The scaffolding approach enabled the teachers to promote pupils' self-directed learning. The teachers explained that they facilitated self-directed learning by not answering pupils' questions directly. Instead, they addressed a relevant context (case 1), asked questions in return (case 3), and talked about pupils' own ideas for investigations (case 4). The case 2 teacher emphasised the difficulty of determining the amount of teacher guidance to facilitate pupils' self-directed learning. When pupils made a choice that was not ideal, but could be a learning experience, she tried to limit her support. The attention to self-directed learning in the interviews was confirmed by the audio material. However, the audio material also included conversations in which the teachers answered pupils' questions without promoting their self-directed learning.

The teachers perceived the hard scaffolds as clear and very useful to clarify and discuss the inquiry process with pupils. According to the teachers, the soft scaffolds provided opportunities to refer to hard scaffolds when pupils designed and conducted their investigations. However, the case 4 teacher stressed the importance of adding pictures and exercises to hard scaffolds that consisted mostly of textual information (the scaffolds in phases 4 and 5). In addition, the teachers of cases 1 and 2 suggested to use activating sentences, such as 'Our hypothesis is … ', instead of providing information about what a hypothesis is without activating pupils.

Discussion and implications

In this study, we investigated how teacher implementation of hard and soft scaffolds contributed to pupils' understanding of the inquiry process and their self-directed learning during open inquiry in primary schools. In all four lesson modules, two on science topics and two on a philosophical theme, the teacher was able to provide activities and explanations that engaged pupils in formulating and answering research questions during their own inquiries. The implementation of the hard and soft scaffolds resulted in a shared guidance of the inquiry process by the teacher and her pupils. After the teachers in the four cases had prepared the inquiry process by introducing each hard scaffold, the pupils engaged with the scaffolds by applying them to their own inquiries, and designed, conducted, and evaluated their own investigations. The teachers used the hard scaffolds to provide explanations and to reflect on pupils' inquiries. However, in addition to referring to hard scaffolds, the teachers answered pupils' questions without promoting their self-directed learning. These findings are in line with the study of Zion et al. (2007) in which teachers participated in workshops about open inquiry, but were observed to use structured and guided inquiry within their lessons as well. It was suggested that additional professional development was needed. Similarly, in our study, the lack of experience with open inquiry and implementation of hard and soft scaffolds could have contributed to each teachers' decision to not always refer to hard scaffolds, but directly answer pupils' questions instead.

The implementation of six hard scaffolds and two soft scaffolds contributed to pupils' understanding of the conceptual, epistemic, social, and procedural domain of scientific knowledge within the different phases of inquiry. Pupils used the scaffold 'poster with inquiry phases' to understand the process of open inquiry (epistemic domain) and the scaffold 'question wall' to formulate initial questions related to the project theme (conceptual domain). They formulated and evaluated research questions by means of the scaffold 'question machine' (procedural domain). Subsequently, they used the scaffolds 'recording data' and 'difference between results, conclusion, and discussion' to organise their data (procedural domain) and process results, draw conclusions, and evaluate their investigations (procedural and epistemic domain). Finally, they composed and gave a clear research presentation (social domain) in which they included the elements of scientific inquiry on the scaffold 'presenting an inquiry'. These findings resemble results of other studies in which scaffolds contributed to pupils' understanding of (domains of) scientific knowledge and the application of this knowledge to their own inquiries (e.g. Sandoval & Reiser, 2004; Saye & Brush, 2002; Simons & Klein, 2007). The study of Simons and Klein, for example, showed that pupil achievement in problem-based projects increased when they were obliged or could choose to use scaffolds compared to when no scaffolds were provided.

The hard scaffolds 'question machine' and 'presenting an inquiry' were specifically valued by the teachers and their pupils. These scaffolds activated pupils to improve their research questions and presentations, whereas translating scaffolds with a high information load to pupils' inquiries was not self-evident. In addition, hard scaffolds that activated pupils were combined more often with soft scaffolding by both the teacher and the pupils than hard scaffolds that informed pupils about elements of an inquiry. Since the teachers in the current study had little experience with inquiry-based learning, it might have been easier and less time consuming to support pupils by directly providing answers instead of referring to informative scaffolds that needed additional translation to pupils' investigations. Moreover, soft scaffolding is not easy to implement by teachers. In the study of Saye and Brush (2002), for example, a teacher continued to have difficulty providing soft scaffolds after guiding and evaluating a problem-based lesson module that included hard and soft scaffolds. Another study illustrated that even after extensive training, providing soft scaffolds was challenging for teachers (Van de Pol et al., 2014).

In our previous study, we developed a pedagogical framework in which phases of inquiry were combined with specific domains of scientific knowledge to facilitate teacher guidance of open inquiry (Van Uum et al., 2016). Since the framework provided guidelines but lacked materials that teachers could use in their classrooms, the current study focused on developing hard and soft scaffolds. The key finding of this study is that pupils' scientific knowledge and skills to direct their own inquiry process can be promoted by implementing activating hard scaffolds and additional soft scaffolds during open inquiry. In a subsequent study, we will use these insights to develop a professionalisation programme. We will investigate whether this programme improves teachers' knowledge of and attitude towards inquiry-based learning. By professionalising teachers thoroughly, we expect them to implement hard and soft scaffolds to contribute to pupils' self-directed learning and understanding of the inquiry process.

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Appendix

Content of and teacher guidance in each classroom inquiry project

Case 1: Higgs

The teacher introduced the project by showing a video about the determination of the Higgs particle in the particle accelerator at CERN, the European Laboratory for Particle Physics. Pupils observed that particles can be investigated by acceleration and collisions. Subsequently, the teacher explored the topic of Higgs with her pupils in different activities. For example, she enabled pupils to understand how Higgs provides weight to particles by organising an activity in which one pupil (a heavier particle) needed to collect more autographs of the remaining pupils in the classroom (the Higgs field) than another pupil (a lighter particle). The heavier particle gained more mass while it was slowed down by the Higgs field than the lighter particle. Furthermore, the teacher explained that the Higgs field was invisible. Therefore, in addition to acceleration and collisions, weight and invisibility were possible topics for investigation. Subsequently, the teacher supported the formulation of research questions by pupils, such as: 'What falls faster, a marble or a tennis ball?' The teacher enabled her pupils to conduct their research, to draw conclusions and to compose a research presentation. Finally, her pupils presented their research to other classmates and to their parents.

Case 2: The world upside down

To introduce the project, the teacher enabled her pupils to colour pieces of an art work to show that both the individual pieces and the total work can be observed and appreciated. Subsequently, the teacher invited a researcher to the school to discuss philosophical questions. Furthermore, the teacher explored the topic with her pupils by dividing them into groups that spoke different languages and had their own goals, but needed to trade with the other group. In addition, she provided activities, such as discussing the discipline that adults experienced in their education compared to the discipline in current classrooms. Her pupils formulated research questions, such as: 'Are adults or children more willing to donate an amount of money to a charity?' After designing and conducting the investigations, pupils drew conclusions and presented their research to their classmates. A university visit enabled them to explain their investigations by means of PowerPoint presentations and research posters to an audience of researchers.

Case 3: The world upside down

The introduction of the project, the visit of a philosopher, and a group activity concerning trading with people from different cultural backgrounds were guided by both the teachers of cases 2 and 3 together. To further explore the topic with her pupils, the teacher of case 3 focused on differences in viewpoints. In one of her activities, pupils were instructed to construct a hat as fast as possible. Half of the pupils received materials inside a big bag and the other half received the bag apart from the materials. The pupils observed that their classmates in the second group became aware of the possibility to use the entire bag as a hat more often than in the first group due to a difference in viewpoint. An example of a research question formulated by pupils in case 3 is: 'Do foreign people think differently about certain topics than Dutch people?' The final part of the project, from conducting the investigations onwards, is the same as in case 2.

Case 4: Networks in the brain

The upper primary school teachers of the school of case 4 all guided an IBSE project in their classrooms. They introduced the topic together by performing a play about manipulating different parts of the brain during brain surgery and showing effects of these manipulations on movements of the body. Furthermore, they presented games in which pupils used different parts of their brains and became aware of brain functions. After the introduction of the project, the teacher of case 4 enabled her pupils to explore the topic by means of watching videos about the working of the brain, and discussing brain areas with different functions. Furthermore, she provided hands-on activities regarding optical illusions to show that the brain can be tricked. An example of a research question of pupils is: 'Can you remember things better when you read them or when you hear them?' After the formulation of the research questions, pupils designed and conducted their investigations and drew conclusions. Finally, they presented their research to their classmates and parents.