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Inquiry-based science education: towards a pedagogical framework for primary school teachers

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ABSTRACT
Inquiry-based science education (IBSE) has been promoted as an inspiring way of learning science by engaging pupils in designing and conducting their own scientific investigations. For primary school teachers, the open nature of IBSE poses challenges as they often lack experience in supporting their pupils during the different phases of an open IBSE project, such as formulating a research question and designing and conducting an investigation. The current study aims to meet these challenges by presenting a pedagogical framework in which four domains of scientific knowledge are addressed in seven phases of inquiry. The framework is based on video analyses of pedagogical interventions by primary school teachers participating in open IBSE projects. Our results show that teachers can guide their pupils successfully through the process of open inquiry by explicitly addressing the conceptual, epistemic, social and/or procedural domain of scientific knowledge in the subsequent phases of inquiry. The paper concludes by suggesting further research to validate our framework and to develop a pedagogy for primary school teachers to guide their pupils through the different phases of open inquiry.

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Introduction

Inquiry-based science education (IBSE) is regarded as an inspiring way of learning science as it focuses on pupils' own interests and stimulates active learning by enabling pupils to conduct their own investigations (Braund & Driver, 2005; Murphy & Beggs, 2003; Rocard et al., 2007). Since addressing pupils' motivation and own interests positively influences their achievements (Tella, 2007), IBSE is viewed as an effective approach for learning scientific concepts and understanding the nature of science (NOS) in which the process of inquiry is key.

The pedagogy of IBSE allows pupils to develop their conceptual understanding of scientific phenomena (Minner, Levy, & Century, 2010; Schroeder, Scott, Tolson, Huang, & Lee, 2007) and their inquiry skills, such as formulating a research question (Zion, Cohen, & Amir, 2007). Moreover, pupils learn about the way scientific knowledge is constructed

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(Khishfe & Abd-El-Khalick, 2002) and develop an image of the social practice of scientists (Mercer, Dawes, Wegerif, & Sams, 2004). IBSE has been suggested to positively affect learning outcomes of students by means of enabling open inquiries (Berg, Bergendahl, Lundberg, & Tibell, 2003; Liang & Richardson, 2009). In open IBSE, teachers encourage pupils to conduct a self-designed, interest-guided inquiry in order to answer their own research question. During this process, the important role of the teachers is directed towards facilitating, supporting and supervising their pupils (Zion et al., 2007).

Unfortunately, implementing IBSE in primary school classrooms is not self-evident. Zion et al. (2007) indicated that teachers experience difficulties in guiding pupils through the process of inquiry, for example, regarding the formulation of a research question (Peeters & Meijer, 2014) and the design of an investigation (Yoon, Joung, & Kim, 2012). To cope with feelings of insecurity about science education, teachers rely on methods and materials whereby pupils primarily follow instructions (Harlen & Holroyd, 1997). This implies a top-down approach in which teachers provide the research question and design of the investigation, and contradicts a bottom-up open inquiry process in which pupils design and conduct their own investigations (Windschitl, 2003).

To aid teachers in facilitating open inquiries of pupils, this paper focuses on the following central question: How can primary school teachers support their pupils during open IBSE? Based on a literature study, we first elaborate four domains of scientific knowledge which are important to be addressed during open IBSE (Duschl, 2008; Furtak, Seidel, Iverson, & Briggs, 2012). Subsequently, we describe seven phases that together comprise an inquiry cycle, for example, designing and conducting an investigation, based on Van Graft and Kemmers (2007). With our paper, we aim to translate this conceptual framework of domains of scientific knowledge and phases of inquiry into a pedagogical approach to be used within classroom practice. Our hypothesis is that pedagogical interventions of teachers should focus on supporting pupils' learning process by addressing specific domains of scientific knowledge in each phase of inquiry. We investigated which combinations of domains of scientific knowledge and subsequent inquiry phases proved to be successful in guiding pupils during the process of open inquiry. The resulting 'pedagogical framework' presented in this paper reflects successful teacher interventions observed in seven IBSE projects in classroom practice and can be considered as an example of how open inquiry can contribute to learning in particular scientific knowledge domains and vice versa.

Theoretical framework

Based on a synthesis of research within the fields of learning sciences, science studies and science education, Duschl (2008) differentiated between three domains of scientific knowledge reflecting different levels of scientific literacy (Durant, 1993): 'The conceptual structures and cognitive processes used when reasoning scientifically, the epistemic frameworks used when developing and evaluating scientific knowledge, and the social processes and contexts that shape how knowledge is communicated, represented, argued, and debated' (Duschl, 2008, p. 277). In a review study of inquiry-based teaching, Furtak et al. (2012) added a fourth procedural domain comprising procedures, such as formulating a research question. The four domains are elaborated below and linked to different phases of inquiry (Van Graft & Kemmers, 2007).

The conceptual domain

The conceptual domain (Duschl, 2008; Furtak et al., 2012) of science consists of a 'body of knowledge that represents current understanding of natural systems' (National Research Council, 2007, p. 26), such as the phenomenon of light (Mumba, Mbewe, & Chabalengula, 2015). Research and practical experience suggest that pupils need conceptual knowledge regarding the topic of investigation in order to perform inquiry procedures, such as formulating research questions (Peeters, Meijer, & Verhoeff, 2014; Zion et al., 2007).

The epistemic domain

The epistemic domain refers to NOS and the way scientific knowledge is generated (Duschl, 2008; Furtak et al., 2012). NOS indicates a person's beliefs about what scientific knowledge is, for example, whether it is tentative or not and based on creativity (Lederman, 1992). In addition, the way scientific knowledge is generated refers to the combination of scientific processes, such as observing and measuring, with 'scientific knowledge, scientific reasoning and critical thinking to develop scientific knowledge' (Campanile, Lederman, & Kampourakis, 2015, p. 207). In the current study, we consider scientific processes as part of the procedural domain, and reflecting on what scientific knowledge is and how it is generated as part of the epistemic domain.

Khishfe and Abd-El-Khalick (2002) compared the National Science Education Standards with Benchmarks for Science Literacy and found corresponding NOS aspects for primary school pupils; that is, understanding that scientific knowledge is tentative, includes creativity, is based on empiric findings and differentiates between observation and inference. Furthermore, according to Furtak et al. (2012) and Sandoval (2005), it is important for pupils to connect their own investigations to the way real scientists work and generate knowledge.

The social domain

The social domain of science (Duschl, 2008; Furtak et al., 2012) refers to important scientific dispositions of researchers, such as critically reviewing their own work and that of others, and to share findings (Van der Rijst, 2009). Although researchers compete with each other for grants and funding and develop alternative and sometimes contrasting theories, they often work together in research projects and elaborate on each other's theories and results, published in peer-reviewed journals.

In primary schools, research collaboration and communication can be addressed by assigning different roles and responsibilities to pupils during group work and by focusing on collective activity and shared meaning (Tolmie et al., 2010). In collaborative inquiry, exploratory talk is important to improve pupils' scientific reasoning and their formulation of constructive feedback. In exploratory talk, 'everyone is asked to make their reasons clear' and 'challenges and alternatives are made explicit and are negotiated' (Mercer et al., 2004, p. 362). Furthermore, when communicating their findings to others, pupils need to know how to clearly explain their actions and decisions regarding their investigation to an audience (Peeters et al., 2014).

The procedural domain

Following Furtak et al. (2012), we distinguished a fourth procedural domain to address inquiry procedures, such as formulating research questions and drawing conclusions to answer the research questions. The added value of the procedural domain is attention for these procedures within the phases of inquiry. Procedures can be executed without reflection on the generation of scientific knowledge. The latter is addressed in a separate epistemic domain. By distinguishing these domains, both procedural and epistemic knowledge are attended to. Boekaerts and Simons (1995) described procedural knowledge as knowing how to use knowledge, while others have described it as 'knowing how to proceed' (Glaesser, Gott, Roberts, & Cooper, 2009, p. 597). Both perspectives are included in our conception of procedural knowledge.

In primary education, pupils need support by their teacher to conduct inquiry procedures. They, for example, find it difficult to formulate a research question and to draw conclusions based on their own research data (Peeters et al., 2014; Zion et al., 2007).

Phases of inquiry

The four domains reflect the scientific knowledge to be addressed during inquiry projects (Duschl, 2008; Furtak et al., 2012). Our pedagogical framework aims to guide teachers in addressing the different domains during the subsequent phases of an inquiry process. In the Netherlands, the IBSE phases of Van Graft and Kemmers (2007) are increasingly used by curriculum developers and teachers and will be addressed in the current research study. This inquiry cycle resembles the synthesis of phases of inquiry of Pedaste et al. (2015), but comprises seven instead of five phases: introduction, exploration, designing the investigation, conducting the investigation, conclusion, presentation/communication and deepening/broadening.

Method

In this study, we explored whether and how teachers addressed four domains of scientific knowledge in each IBSE phase to successfully support their pupils' investigations. Our assumption, based on experiences with open IBSE projects, was that supporting pupils in an open inquiry process requires specific focus on different domains of scientific knowledge during the subsequent phases of inquiry. To develop a pedagogical approach that addresses the four domains in the process of open inquiry, we observed in-class teaching strategies. We used our theoretically based framework of phases and domains to analyse video clips of open IBSE projects in primary schools. By analysing these video clips, we intended to clarify for each IBSE phase which domains of scientific knowledge were addressed by the teacher during open IBSE and what the effect was of these teacher interventions.

Case selection and research subjects

In the Netherlands, there are 12 regional expertise centres that focus on promoting and implementing IBSE in primary education. We selected one of these so-called

Science Education Hubs: Science Education Hub Radboud University (WKRU), because it has numerous experiences with open IBSE. WKRU has been the first Science Education Hub in the Netherlands under the auspices of the National Platform Science and Technology since 2009, and the Royal Netherlands Academy of Arts and Sciences since 2012. Within WKRU several educational open IBSE projects have been developed for primary school pupils of 10–12 years old. These projects have been developed according a design approach by translating research of Radboud University into open IBSE activities in assembled project teams of scientists, teacher trainers and in-service and pre-service primary school teachers. The developed pedagogical approach has been tested and adjusted in classroom practice. The participating teachers acquired content knowledge regarding relevant concepts, the generation of scientific knowledge and important inquiry procedures by means of discussions with researchers and WKRU members in their project team. Furthermore, they acquired pedagogical knowledge regarding IBSE. They did not have any prior experience with IBSE.

We analysed videos of seven of these open IBSE projects in different primary schools using our analytical framework of open inquiry phases and domains of scientific knowledge. Video recordings of each project consisted of approximately eight hours of film of five to nine inquiry-based lessons showing teacher interventions and pupils' responses. In addition, during group work an interviewer asked pupils to describe, explain and reflect on the design and conduction of their investigations. Natural scientists were involved in five of the projects: DNA and heredity; Perception, action and movement; Graphene; Anxiety and Behaviour. Social scientists and philosophers participated in two projects: Addiction and Dangerous opinions. In Appendix 1, these projects are elaborated.

Qualitative analysis

In analysing the video fragments we, first, labelled the different IBSE phases. Within each labelled phase, we selected fragments of pupils' comments and/or teacher's comments regarding one of the four domains of scientific knowledge. Subsequently, we identified whether the pedagogical interventions by the teacher could be considered successful or not. In order to determine this we, first, looked at the immediate consequences within each fragment. Second, we analysed the transcription of the remainder of the inquiry phase, including the selected fragment. Finally, we analysed the subsequent inquiry phases to find additional consequences. We defined the success or lack of success as pupils' comments of (mis)understanding or their (in)ability to proceed with the subsequent phases of inquiry. An example of a successful pedagogical intervention regarding the social domain is a comment by the teacher to improve a presentation and subsequently, seeing the improvement in the pupils' presentation. An example of an unsuccessful pedagogical intervention in the procedural domain is an intervention to improve the formulation of a research question, after which pupils do not take into account the teacher's comments and remain confused about their next action. After analysing each project, the results of the different WKRU projects were compared to find any patterns regarding (un)successful pedagogical interventions.

Results

Table 1 presents a quantitative overview of the domains of scientific knowledge addressed by teachers and pupils during the subsequent phases of inquiry in all seven projects. We used this quantitative overview as a point of reference for the qualitative data analyses. In the introduction phase, the teachers focused on the epistemic domain and discussed the connection between the classroom project and authentic scientific investigations with their pupils. In the exploration phase, the teachers elaborated on the conceptual domain by means of videos, discussions and hands-on science activities, and pupils developed a deeper understanding of the project theme. When pupils designed their investigations, teachers mostly addressed the procedural domain and also the social and epistemic domain to prepare pupils for the actual investigations. In this phase pupils formulated a research question and discussed within their research groups how to design a valid and reliable investigation. While conducting the actual investigations, the teachers explained procedures, such as taking correct measurements, when pupils made mistakes or were inaccurate in using these procedures. In the conclusion phase, teachers focused on the procedural domain to explain the procedure that supports drawing a conclusion. Furthermore, they addressed the epistemic domain by differentiating between observations and inferences. The conceptual domain was only referred to by pupils during their group work without interference by their teachers. In the presentation/communication phase, the teachers mainly focused on the social domain to improve pupils' research presentations. Finally, in the deepening/broadening phase, teachers and their pupils visited Radboud University to discuss important concepts related to the project theme and considerations regarding the design of valid and reliable investigations with actual scientists.

Based on the quantitative overview in Table 1, we analysed the data qualitatively as elaborated in the following paragraphs.

Phase 1: introduction

The goal of the introduction phase is to confront pupils with a problem or phenomenon connected to an authentic research practice to excite pupils' curiosity and increase their epistemic understanding about open inquiry. As the following quote illustrates, within the context of WKRU the teachers referred to research conducted at Radboud University.

Teacher: Certain scientific investigations, in other words a research which a scientist conducts, almost never ends up at primary schools. (…) Together with

Table 1. Relative amount of references made to domains of scientific knowledge during each phase of inquiry by teachers and pupils in all seven projects (see Appendix 1).

		Domain			
Phase	*N*	Conceptual	Epistemic	Social	Procedural
Introduction	12	25.0	58.3	16.7	0
Exploration	195	73.3	12.8	2.6	11.3
Designing the investigation	358	13.4	20.4	16.8	49.4
Conducting the investigation	58	1.7	8.6	5.2	84.5
Conclusion	42	19.0	26.2	2.4	52.4
Presentation/communication	101	6.9	7.9	66.3	18.8
Deepening/broadening	36	33.3	44.4	11.1	11.1

> the Science Education Hub we are going to try to implement scientific research in primary school projects. Because we think that you can learn a lot by doing this.

By referring to an authentic research practice, pupils gained interest and developed an epistemic understanding to work on a real problem as scientists do. Although in the current phase most teachers did not provide a detailed description of real scientific practices, they were able to refer to these practices in subsequent inquiry phases.

Phase 2: exploration

The objective of the exploration phase is to connect the phenomenon under investigation to pupils' prior knowledge. The inquiry is directed towards formulating questions that guide further investigation. The teachers of the WKRU projects accomplished this by asking questions that evoke a response and asking clarifying and explanatory questions to retrieve prior knowledge regarding the project theme. The teachers improved conceptual understanding by connecting concepts to relevant everyday contexts and combining hands-on science activities with minds-on reflections about these activities. For example, in the graphene project (see Appendix 1), the teacher showed a video to introduce different characteristics of graphene and asked her pupils to construct a collective concept map regarding these characteristics. Since graphene is a crystal, she showed a second video about the characteristics of crystals. Furthermore, the teacher compared the structure of graphene to chicken wire. Subsequently, she asked her pupils to construct a 3D visualisation of graphene with cocktail picks and wine gums. The structure of graphene was discussed, based on the collection of pupils' own 3D models connected to their knowledge of the structure of crystals. At the end of the exploration phase, the teacher asked her pupils to write down what they had learned about the project theme and what questions remained unanswered. For example, pupils described different characteristics of graphene they knew. In addition, they formulated a question about how to collect graphene. Pupils' remaining questions provided a base for their own research questions in the next inquiry phase of designing the investigation.

Similar activities were provided by the teachers of the other projects, such as the project on perception, action and movement (see Appendix 1), to improve pupils' understanding in the conceptual domain. In the project on dangerous opinions (see Appendix 1), pupils learned about freedom of speech, rules inside and out of the classroom, and opinions that might be regarded as 'dangerous'. In this project a group of pupils struggled with the formulation of their research question.

Pupil 1: We did not really have a research question, but …
Pupil 2: Formulating a research question took us very long. We had a very difficult subject. And at a certain moment the teacher allowed us to investigate: how do people look at power relations and what do they think about it?
Pupil 1: And we were allowed to construct a questionnaire etc.

The second pupil in the fragment referred to the difficulty of their assigned research topic of 'power relations' which was not explicitly discussed in the exploration phase.

Subsequently, the teacher did not promote his pupils' conceptual understanding of power relations and allowed his pupils to continue their investigation with the general research question: 'How do people look at power relations and what do they think about it?' As a consequence, these pupils asked their research subjects many different questions about power relations which made it difficult to draw a conclusion. This illustrates the importance of addressing conceptual understanding in the exploration phase to enable pupils to formulate a specific instead of general research question and to proceed with subsequent inquiry phases.

Phase 3: designing the investigation

The design phase of the inquiry is focused on formulating research questions, composing a research plan and constructing or collecting instruments for measurements. In going through these different steps, it is important for teachers to address the procedure of formulating a research question, to discuss how to design a valid and reliable investigation, such as determining the number of research subjects and measurements, and to address social issues regarding collaboration and communication in pupils' research groups.

The teachers in the projects on addiction (see Appendix 1) and dangerous opinions scaffolded the procedure of formulating a research question by means of a question machine (Peeters et al., 2014). The developed question machine comprises a written scaffold depicting a flow chart with criteria for research questions, such as: 'The question is singular' and 'The question is specific and measurable' (see Appendix 2). When a question fails to meet one of the criteria, pupils need to adjust it. After pupils in the project on addiction had practised by testing some exemplary questions, they used the machine to improve their own research question.

Pupil 1: What happens when you drink three beers every day?
Pupil 2: [Points at the question machine] It is not a question that you can look up. It is a singular question. It is quite a good question, it will come out [of the question machine], I think.

As illustrated, the question machine stimulated pupils to check the quality of their formulated research question and improved their procedural understanding. However, pupils of the project on dangerous opinions that posed the question: 'How do people look at power relations and what do they think about it?' failed to formulate a question that met the criterion of being specific enough. As mentioned in the exploration phase, these pupils asked their research subjects many different questions and were not able to present a conclusion regarding their research. This illustrates the importance of a well-formulated research question guiding the design of the research.

To answer the research question, the next step was to design an investigation. Teachers or invited researchers explained the design criteria of a proper investigation and questioned pupils about epistemic considerations, such as the number of research subjects and measurements to include in their investigation. The following example regarding the project on behaviour (see Appendix 1) illustrates this.

Researcher: Say I would like to know the difference between boys and girls in impulsiveness, then I could test you [boy] and you [girl]. If I find that you are more impulsive than you. Can I say that all girls are more impulsive than all boys?
Pupils: No.
Researcher: And if I take ten boys and ten girls, can I say it then?
Pupils: No.
Researcher: No, but I can say it with a little bit more certainty. And when I take all boys and girls of the Netherlands? Can I say then a bit more about whether girls or boys are more impulsive?
Pupil: Of the Netherlands you can.
Researcher: Exactly. Of the Netherlands you can. (…) It is something that you have to think about. How many people you want to test.

The considerations regarding the number of research subjects in the previous example influenced the design of pupils' research. In the WKRU projects there were groups of pupils that included many research subjects, but also groups that designed a quantitative research, but included only two or three research subjects. In the subsequent example, a pupil in the project on anxiety (see Appendix 1) was asked about the changes she would make in a future investigation.

Pupil: I think we would ask more children. Because now we have only asked ten. Therefore, we wrote down: so these ten children of year five are more afraid when they do not know what is inside the box. We could not write down year five [entirely], because we do not know that.

This pupil generated valuable insight in the epistemic domain by recognising the importance of sufficient research subjects after she had conducted her research. Because not all pupils will develop these insights on their own, teachers should explicitly reflect on research designs to stimulate pupils' understanding of the epistemic domain.

In addition to procedures and epistemic considerations, social competences such as collaboration and communication were important to address in the current phase of inquiry. In four of the seven projects, the teachers facilitated pupils' collaboration by distributing different roles among each research group of pupils, such as chairman and minutes secretary. In the following example, the teacher of the project on dangerous opinions used these roles to call attention to the responsibilities of the chairman.

Teacher: But you should not discharge questions by any means. You can also adapt questions.
Pupil: Yes, but that is what I want.
Teacher: Who is the chairman?
Pupil: I am.
Teacher: So finally you say: now I'm going to decide. This question we are going to consider one more time together.

The example shows the teacher referring to the role of chairman to help the group decide on a research question.

In the project on anxiety, a group of pupils experienced difficulty to resolve a disagreement about the selection of research subjects without any teacher support. Such a disagreement enables teachers to focus on the social competence of pupils by discussing how to resolve the disagreement together and to proceed with their inquiry.

Phase 4: conducting the investigation

The goal of the current phase of inquiry is data collection. During data collection, it is important to measure precisely and to take notes in a structured way. As soon as pupils experienced problems in the procedural domain, the teachers in the WKRU projects addressed these problems. In the project on graphene, for example, pupils measured the weight of bricks on top of different objects to find out how many bricks the particular object could hold before braking. They estimated the weight of one brick, observed how many bricks were needed and worked out the entire weight of the different bricks together. During their investigation, an observing teacher asked pupils how they could measure more precisely and explained the use of a scale. In the other projects we observed pupils measuring temperature, time, heartbeat, etc., and, for example, writing down answers when they interviewed research subjects. As the following example regarding the project on behaviour illustrates, not all groups of pupils paid sufficient attention to these procedures.

Cameraman: Do you have a conclusion yet? (…)

Pupil 1: We have scored how many [research subjects] went dancing. And now we are going to add it up. Because we have girls and boys. And we will add that up.

Pupil 2: Only it was not going so well with the girls and boys. Because they were grouping all together (…). You quickly score one of those [group of girls or group of boys].

Pupil 1: Yes, we could have better written down the two songs and then score how many were dancing on each song. But, we could not really have known that.

After their investigations these pupils noticed the drawbacks of trying to score boys and girls when they were grouping together. The pupils realised that it would have been better to focus on the amount of pupils dancing on each song than trying to score boys and girls separately. To extend pupils' procedural understanding of making correct measurements and taking notes, it is essential for teachers to explain, practise and reflect on these procedures with their pupils.

Phase 5: conclusion

To draw a conclusion, it is important for pupils to connect the data to their research question and to realise that results and their own opinions should be distinguished. The teachers of the projects on addiction and dangerous opinions explicitly addressed a procedure to support drawing a conclusion in the current phase by referring to relevant everyday contexts. The teacher of the project on dangerous opinions first explained how pupils could categorise their detailed results.

Teacher: So if you were processing your data and you had a category of people between 30 and 50 [years old] and you have got 36 marks [research subjects in this category], the most of all, then you can say: well, people in this category … Just look at your data. The most, least, most prominent.

Subsequently, the teacher provided an example from his own teaching practice and discussed how to draw a conclusion by linking data to a research question.

Teacher: I want to know: has year 6 in the last months advanced in spelling? Well, when I look at many results then I would have to conclude: yes, year 6 has advanced a little bit in her spelling level in the last few months. Is that a good conclusion? Yes, that is a good conclusion, because I can read it in my data.

The teacher explained the importance of linking data to the research question in order to draw a conclusion. As the subsequent example from the project on addiction illustrates, without an explanation regarding how to draw a conclusion pupils might make mistakes.

Teacher: Yes indeed, you are going to look at: what is really the conclusion? What is really the answer to my research question? (…) When you have an investigation in which you want to compare girls and boys. Who ride their bikes more: boys or girls? (…) What data, where do you have to look at? (…)
Pupil: Sometimes it is also a little bit due to age. That is also something you have to look at, right?
Teacher: No, because what was the research question?
Pupil: Oh, like that.
Teacher: In your conclusion you are going to answer your question. And not all other things, exactly what you mentioned, which might be interesting as well.

The pupil in this example thought it would be best to draw a conclusion based on data that were not directly relevant. Subsequently, his teacher promoted procedural understanding by referring to the research question and highlighting the importance of answering this question.

In addition to the procedural domain, the teacher of the project on dangerous opinions addressed the epistemic domain by questioning his pupils about the difference between their observations and their own opinions. He provided explanations to make sure that pupils did not blend these together. Although in the different projects most of the pupils did not blend their observations and opinions, the following example of the project on behaviour shows that not every pupil understood this difference.

Cameraman: Do you already have your conclusion? Or not yet?
Pupil 1: The conclusion is that children quicker touch candy. Right?
Pupil 2: No, bouncing balls.
Pupil 3: Toys.

Pupil 1: Oh, right.
Pupil 4: They touch toys more quickly than [candy].
Pupil 5: I still think that the marshmallow is more tempting.

The pupil in the example preserved her opinion regarding the temptation of candy over a toy, although the results revealed that research subjects touched the toy more often than the candy. It is unclear whether this pupil is an exception or that more pupils had difficulties distinguishing their opinions and their results, because some groups of pupils only presented their results without discussing their opinions about the generation of results. Therefore, teachers should explain the distinction between results and opinions and should ask pupils to clarify their opinions to gain insight into pupils' reflections regarding their own research.

Phase 6: presentation/communication

After conducting the investigation and drawing conclusions, the intention of the current phase is pupils' communication of their results to others. It is important that pupils present their investigation and results in a clear and comprehensible way. In all observed WKRU projects, pupils improved their understanding of the social domain by presenting their research to their classmates and/or their parents, or to researchers of Radboud University. They made use of PowerPoint, posters, movies or plays to illustrate their research. In the preparation of the presentation or directly after pupils presented their research, the teachers asked clarifying questions about pupils' presentation and facilitated reflection through feedback on how to present research in a clear and organised way. The teacher of the project on behaviour discussed how to clarify parts of the presentation during its preparation.

Pupil 1: [Reads part of the PowerPoint out loud]: The subject is whether he/she is more lively at home or at school.
Teacher: Who is meant with he or she? Because that is something the parents do not know, right?
Pupil 2: Write along: your son/daughter.
Pupil 1: It says that on top.
Teacher: Yes, but you have to refer back to that. Otherwise it is not clear.

The teacher asked about the meaning of 'he or she' in order to improve the content of the presentation of the pupils. The teachers of the projects on addiction and on DNA and heredity (see Appendix 1) commented on the presentations of pupils directly after the pupils presented their research and asked their pupils to give each other tips and compliments. This enabled pupils to reflect on their presentation and to take into account the remarks for future presentations. The subsequent presentation of the project on anxiety is shorter and less structured than the average presentation that pupils composed, but was placed here to show that it lacks information.

Pupil 1: Our research question is: what is the top three of all groups in the [name of the school].
Pupil 2: These are our results. [The pupils show a poster with the results of each group and describe these results].

Pupil 1: We really liked to work on it.
Pupil 3: It is only a shame that it [the project] has ended already.
Pupil 4: How did we investigate this?
Pupil 1: We went along the classrooms and asked whether they could write down their top three about things they are afraid of. At the kindergarten we made a letter for the parents and gave it along with the pre-schoolers. And we asked if they wanted to fill it in with their parents.
Pupil 2: And this was our research (…) [incomprehensible].

The quoted pupils forgot to mention crucial elements of a research presentation, such as a hypothesis, conclusion and discussion about limitations and recommendations regarding their own research. Therefore, teachers should address these important elements during the preparation of the presentations and reflect on these elements after pupils have presented their research.

Phase 7: deepening/broadening

In the final phase of inquiry, the goal is to reflect on the inquiry process and to deepen or broaden understanding of the project theme. In half of the WKRU projects, pupils visited a lab at the university, or spoke with scientists who visited the participating school. As part of these visits, scientists discussed the concepts within their research studies and talked about the epistemic decisions they made. Pupils presented their own research and answered questions of the scientists. In addition to a site visit to a university, there are other options to deepen or broaden pupils' understanding, for example, group discussions regarding the domains of scientific knowledge and questions that remain unanswered. Ideally, these reflections lead to a new cycle of IBSE.

Conclusion

The results show that it is important for teachers to support pupils' learning process by addressing specific domains of scientific knowledge in each phase of inquiry. Table 2 represents a pedagogical framework based on these results. This framework serves as an example of how the focus of the teachers in the WKRU projects shifted from one domain of scientific knowledge to another during the different inquiry phases. In these open inquiry projects teacher interventions, based on specific domains of scientific knowledge addressed in the subsequent phases of inquiry, contributed to pupils' understanding of open inquiry. For example, in the exploration phase teachers addressed the conceptual domain by questioning pupils to retrieve prior knowledge and improved understanding about the project theme by referring to relevant everyday contexts and connecting hands-on science activities with minds-on reflections about these activities. Subsequently, pupils were enabled to differentiate between their acquired knowledge and their remaining questions. We observed that when the teachers paid attention to specific domains in their linked phases, pupils were enabled to proceed within and between inquiry phases. However, teachers should be mindful of other domains of scientific knowledge in each IBSE phase as well, depending on the specific context of the project.

Table 2. The contribution of addressing specific domains of scientific knowledge in the subsequent inquiry phases.

	Phase	Domain	Examples of teacher interventions	The contribution to the learning process of pupils
1	Introduction	Epistemic	Promoting pupils' enthusiasm regarding the process of open inquiry by referring to authentic research practices	Understanding the context of scientific research and being enthusiastic about the process of open inquiry
2	Exploration	Conceptual	Questioning pupils to retrieve prior knowledge and improving understanding about the project theme by linking concepts with relevant everyday contexts and providing hands-on science activities combined with minds-on reflections	Differentiating between their acquired knowledge and the knowledge they wanted to acquire regarding the project theme in order to formulate a research question in the next phase of inquiry
3	Designing the investigation	Procedural	Scaffolding the procedure of formulating a research question via a question machine with criteria and examples	Performing the procedure of formulating and adjusting a research question
		Epistemic	Explaining design criteria of a proper investigation and questioning pupils about considerations regarding their research design, such as the number of research subjects and measurements	Considering the number of research subjects and measurements needed to conduct the investigation
		Social	Facilitating pupils' collaboration, for example, by dividing roles such as chairman, and discussing individual responsibilities regarding these roles	Working together during the inquiry process according to their role of collaboration
4	Conducting the investigation	Procedural	Asking and explaining pupils how to measure precisely and how to take organised notes	Making correct measurements and taking organised notes
5	Conclusion	Procedural	Explaining how to draw a conclusion by discussing relevant everyday contexts and referring back to the research question	Referring back to the research question when drawing a conclusion
		Epistemic	Questioning pupils about the difference between results, conclusion and discussion and providing explanations	Differentiating between results, conclusion and discussion
6	Presentation/ communication	Social	Asking pupils to clarify their presentations and facilitating reflection through feedback on how to present the research in a clear and organised way	Explaining the research to an audience via paying attention to the different components of the process of inquiry
7	Deepening/ broadening	Reflection and further elaboration on all domains or specific choices	Visiting a scientific practice or facilitating a visit of researchers to the primary school to reflect on acquired knowledge and to further deepen/broaden the knowledge	Reflecting on acquired knowledge and further deepening/broadening of knowledge

Discussion and implications

The central question in our study is: How can primary school teachers support their pupils during open IBSE? We answered this question by developing a pedagogical framework regarding domains of scientific knowledge and phases of inquiry based on a literature study and video analyses of open inquiry in practice. The constructed pedagogical framework supports teachers in their guidance of pupils through the process of open inquiry.

In the WKRU projects the sequence of domains of scientific knowledge in the different phases of inquiry was as follows: conceptual (phase 2)—procedural, epistemic and social (phase 3)—procedural (phase 4/5)—epistemic (phase 5)—social (phase 6), all domains or specific choices (phase 7). This sequence illustrates the importance of addressing all four domains before phase 4 to build a foundation for successful conduction of investigations by pupils. In the observed IBSE projects, the domains of scientific knowledge were addressed a second time from phase 4 onwards. We suggest a similar focus for other teachers when supporting their pupils during open IBSE to contribute to successful acquiring, processing and explaining the data.

Furthermore, the results show that specific choices for teacher interventions regarding the domains of scientific knowledge within the process of inquiry enabled pupils to proceed through the different IBSE phases. By means of these interventions, teachers were able to foster pupils' understanding of scientific inquiry. They, for example, scaffolded pupils' procedural understanding by explaining and referring to a question machine to help pupils with the formulation of a research question. To address the epistemic domain, teachers referred to authentic scientific inquiry in the introduction phase and questioned their pupils about the generation of scientific knowledge and provided explanations during the design of the research and in the conclusion phase. This enabled pupils to develop an interest in scientific inquiry, to consider the generation of scientific knowledge and to link their own research with that of real scientists (Furtak, 2006; NRC, 2007; Sandoval, 2005).

Conceptual understanding was improved in the exploration phase by teaching strategies, such as questioning (School aan Zet, 2014) and connecting coherent concepts with relevant contexts by focusing on pupils' interests, making real-world connections and linking prior knowledge and experiences to the topics at hand (Schroeder et al., 2007; Van Graft, Boersma, Goedhart, Van Oers, & De Vries, 2009). Moreover, theory and practice were combined by emphasising minds-on aspects of hands-on science activities (Abrahams & Millar, 2008). These teaching strategies enabled pupils to become aware of their current knowledge and their remaining questions, and to formulate a research question in the phase of designing the investigation more easily.

To address the procedural domain in the phases of designing and conducting the research and in the conclusion phase, teachers used strategies, such as questioning (School aan Zet, 2014), providing static scaffolds (Saye & Brush, 2002) and making connections with relevant everyday contexts (Van Graft et al., 2009). They, for example, scaffolded the procedure of formulating a research question by means of a question machine (Peeters et al., 2014). The importance of supporting pupils' conceptual knowledge and procedural skills during open inquiry is recognised by Zion et al. (2007). Without this support, pupils have difficulties to perform inquiry procedures and to proceed within and between inquiry phases.

Finally, via facilitating pupils' collaboration (Johnson & Johnson, 2009) and reflection through feedback (Van der Schaaf, Baartman, Prins, Oosterbaan, & Schaap, 2013), teachers addressed the social domain during the design and the presentation phase of inquiry. This enabled pupils to discuss collaboration (Schroeder et al., 2007; Tolmie et al., 2010) and communication issues regarding their own research project (Mercer et al., 2004). Furthermore, they were enabled to explain their research to others (Peeters et al., 2014). To conclude, we advise teachers to address specific domains of scientific knowledge in the subsequent phases of inquiry and to implement the teaching strategies that are illustrated in our pedagogical framework.

When teachers and researchers use our pedagogical framework, there are certain limitations and considerations to take into account. We will address these and link them to recommendations for future research. First of all, the context of WKRU is important to address. The collaboration of team members of WKRU, primary school teachers, teacher trainers and scientists of Radboud University enabled the construction of thorough and comprehensive open inquiry projects. To validate our framework, we recommend future research to further investigate other open inquiry projects constructed at Science Education Hubs or primary schools.

Second, the way WKRU projects were captured on film has to be taken into account. The primary goal of obtaining the video material of the different projects was to provide teachers with IBSE examples they could use in their own classroom. The film-makers decided to film different groups of pupils and not to focus entirely on actions of the teacher, because something interesting could happen in a group of pupils while the teacher was focusing on another group. Since we analysed the videos and were not present in the classrooms, it is likely that we did not observe all teacher activities that took place when pupils worked together in their research groups. Nevertheless, comments of pupils regarding teacher actions and similarities between the different projects show that the observed videos sufficiently represent teacher and pupil actions. However, for future research we recommend to capture all teacher actions on camera.

Another consideration regarding our study is that the domains of scientific knowledge were only addressed briefly in the introduction phase and just a few teachers paid attention to these domains in the conclusion phase. For future research, it is advised to further investigate the connection between these phases and their currently linked domains. We would expect, for example, that it is important for teachers to address the conceptual domain in the conclusion phase, but in our analysed projects we did not observe teaching strategies regarding the combination of this domain and phase.

Finally, our most important recommendation for future research is to make the constructed pedagogical framework usable for primary school teachers; for example, by providing tools, materials and exercises based on the pedagogical framework for teachers to use within their classroom practice. With a practical version of the framework, teachers will be further enabled to support their pupils during the process of open inquiry.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix 1

Short description of the seven IBSE projects.

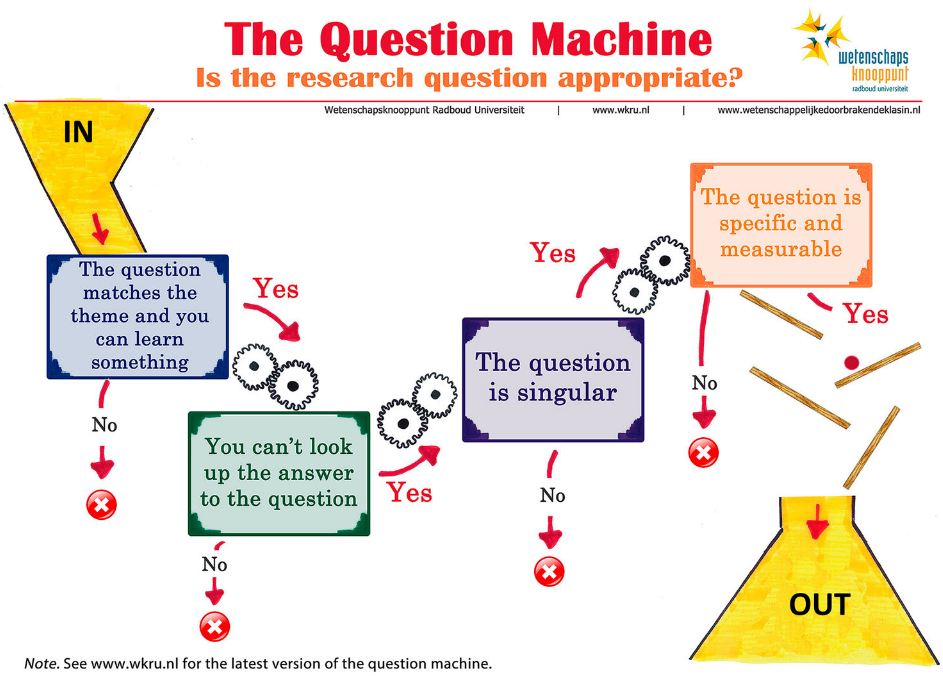
Project	Content
Graphene	By means of watching and discussing videos regarding the characteristics of graphene, pupils learned about this very strong material consisting of a flat surface of carbon atoms. The teacher provided different hands-on science activities, such as constructing graphene with cocktail picks and wine gums. Subsequently, pupils formulated research questions, such as: 'Which object is the strongest: a piece of paper, a wooden stick, a CD or a pen?' After investigation they found, to their surprise, that the piece of paper was the strongest.
Perception, action and movement	Pupils were enabled to engage in hands-on activities, such as balancing a tray with drinks, combined with minds-on reflections by discussing a model that incorporated the concepts of perception, action and movement. An example of a research question formulated by pupils is: 'Can you hit a soccer goal more easily when there is a reference point attached to the goal than without the reference point?' After investigation it turned out that a reference point indeed made a difference. The pupils suggested that soccer coaches can use their results to train professional soccer players.
Dangerous opinions	The teacher and his pupils discussed the importance of rules inside and out of the classroom. By means of different statements, pupils' opinions about freedom of speech were retrieved. Scientists were invited to the classroom to discuss pupils' opinions about philosophers and their theories after being informed about these in short videos. Pupils formulated research questions, such as: 'Is the rule regarding the maximum of 6 minutes to change clothes after gym class respected when there is no consequence attached to this rule?' A consequence indeed made a difference.
Addiction	The teacher provided statements to retrieve pupils' opinions about addiction and peer pressure. The pupils experienced hands-on activities, watched and discussed videos and were informed about real scientific investigations regarding peer pressure. An example of a research question formulated by pupils is: 'Are boys or girls more influenced by peer pressure to drink something which they are not allowed to?' After investigation the pupils found no significant difference between boys and girls.
Behaviour	Pupils were engaged in an experiment and discussed the influence of expected rewards or punishment on remembering a list of objects. Furthermore, they watched and discussed a video regarding the effect of rewards on the behaviour of young children. A research question formulated by pupils is: 'Are kindergarten pupils more temped to touch a sweet or a toy when they are left alone with both?' It came as a surprise that their research subjects were more temped to touch toys than sweets.
Anxiety	The teachers performed a short play about two frightened persons and repeated a real research study with their pupils concerning memory of neutral and scary pictures. A group of pupils in this project investigated the amount of anxiety in research subjects who put their hand inside a box with a known or unknown content. Results of the heart rate monitor showed that research subjects experienced a bit more anxiety when the content of a box was unknown to them.

(*Continued*)

Appendix Continued.

Project	Content
DNA and heredity	The teacher provided hands-on science activities for her pupils to introduce and explore the concepts of DNA and heredity. Pupils, for example, made their own paper DNA sequence consisting of different codes that represented their physical characteristics. Subsequently, they formulated research questions, such as: 'Which physical characteristics does an average child of our school have?' After investigation, this group of pupils concluded that the average child in their school had, among other physical characteristics, blue eyes and blond hair.

Appendix 2



Note. See www.wkru.nl for the latest version of the question machine.