FIFTH-GRADERS' PROBLEM SOLVING ABILITIES IN OPEN-ENDED INQUIRY

Kari Sormunen
University of Joensuu, Finland
E-mail: kari.sormunen@joensuu.fi

Abstract

The goal of this article is to discuss the actual relation between scientific inquiries used in science classrooms and problem solving processes. A model of problem solving ability levels is also introduced. The empirical aim of this study was to explore four fifth-graders' problem solving abilities in related to so called open-ended scientific inquiry tasks. The data was collected in the context of three weekly 60–70 minute sessions in a voluntary science club of 14 pupils. The goal of the sessions was to construct the concept of density with the aid of scientific experimentation. The informants were four pupils paired into two groups. The problem solving process was based on the open-ended inquiry that included five phases: orientation, planning, execution, evaluation, and communication. Both of the pairs were separately observed and video-taped during each of the sessions, and each of the pupils was individually interviewed after each session. All the interviews were based on video stimulation where the crucial parts of the problem solving sessions were reviewed step-by-step with the pupil. The analysis was based on the pupils' problem solving performance: orientation and motivation towards solving the task; aims and actions during the execution; the roles of the pair and the teacher. The problem solving abilities were quite modest, but the results give detailed information on the pupils' own descriptions and explanations related to the different phases of the problem solving process.
Keywords: *primary science education, problem solving, scientific inquiry.*

Introduction

Problem solving strategies play a central role in education, because many tasks performed in daily and professional life require such strategies. Much research has been carried out into problem solving, designing teaching sequences and interventions for certain strategies, and measuring the results of the intervention (see Taconis, Ferguson-Hessler & Broekkamp, 2001). In science education, there has been, however, some confusion about the relationship between problem solving and "investigations" performed at schools (Gott & Duggan, 1995); it is quite obvious that traditional practical approaches in school science with recipe-like tasks offered by textbooks or teacher encourage "operativism" – lacking in scientific meaning and process – and irreflexive memorisation (Freitas, Jiménez & Mellado, 2004).

There are many models of investigation for science education, and some of them could also be seen as models of problem solving in the science classroom (see, e.g., Taconis et al., 2001 and Murphy & McCormick, 1997, for reviews). However, many of the investigative approaches used in science education lack the explication of pupils' problem solving processes and pupils' problem solving abilities. Thus, the first aim of this article is to discuss the investigative approaches in the science classroom that enhance the use of problem solving strategies. The second aim is to introduce a case study with 5th-grade primary pupils, in which their problem solving abilities were studied in the context of open-ended inquiry tasks.

Problem solving in science education

Problem solving can be seen as favouring pupils' motivation, helping them to learn, clarify, apply, and reinforce the principles that they are taught, as well as in itself being a process that develops the pupils' cognitive skills and leads to new learning. However, traditional problem solving in the science classroom is not usually congruent with the aims of problem solving. The traditional sequence for school-level problems in the science classroom could be summarised like Freitas et al. (2004) do: The teacher explains the "theory" (concepts, laws, etc.). The next stage is "practice," in which the teacher poses typical pencil-and-paper "template" problems to illustrate the application of the theory. Sometimes, however, this practice takes place in the laboratory where the pupils follow the recipe given by the teacher to test the theory that they have recently been taught. Usually, they do some of the exercises at the end of the chapter in the textbook, or ones taken from a list prepared by the teacher. Furthermore, it is not uncommon for the teacher to explain problem solving as if everyone knows how to do it. The teacher has seen these problems many times before and has the answers to all of them. This easily leads to the situation in which the teacher explains the problems to the pupils in a clear, linear fashion. This traditional approach usually lacks qualitative prior discussion of the problem and the pupils' analysis of the results. The pupils are not asked to reflect on what they might have really learnt in solving the problem.

When planning an actual problem solving process in the science classroom, both the properties of the problem and the pupils' knowledge and skill base must be taken into account. The properties of scientific problems are, at least in two dimensions, tightly connected to the solver: the familiarity of a problem and the type of cognitive activities required to find the solution (Taconis et al., 2001). Familiarity refers to the situation in which the problem might be a challenge of interpretation and the practice of new skills for one solver, while it is a matter of routine for a person with more experience of the subject. The required cognitive activities – i.e., problem solving skills like problem analysis, planning, execution, evaluation of the process – are dependent on the solver's abilities.

Other types of science problems are those concerning the amount of information included in the problem statement, the complexity of the problem, and whether the problem is closed or open (see Taconis et al., 2001). The problem might contain all the information needed to reach the solution, or conversely the solver needs to find and select information from other sources. The complexity of a problem depends on the number of variables involved, the number of sub-problems to be solved to reach the final solution, and the number of formulae, laws, and principles from which one has to make a choice when planning the solution. The openness of experimental science problems can be defined according to the nature of the task, equipment, method, and results (Hegarty-Hazel, 1990): each of them can be "given", "partly given", or "open"; the openness of the problem depend on the combination of these dimensions. In this particular study, for instance, the problems were open-ended: the task was given, the equipment partly given, the method open, and the results open (cf. the level 2A in Hegarty-Hazel, 1990, p. 375).

Problem solving requires different types of knowledge in the solver's knowledge base (deJong & Ferguson-Hessler, 1996; cf. Taconis et al., 2001). Situational knowledge in needed when recognising and classifying the problem, and when selecting declarative knowledge needed for the solution. Declarative knowledge of facts, principles, and laws of the discipline is needed for drawing conclusions about the situation, and planning and executing the solution. Strategic knowledge of the approach and methods is required in planning, executing, and evaluating problem solving. Furthermore, procedural knowledge is needed for applying declarative knowledge in executing the plan. For instance, open-ended inquiry in the science classroom represents the problem solving process that requires manifold knowledge and skill bases from the pupils. These bases depict high-order cognitive states of a problem solver.

Motivation is an important factor in problem solving processes in the classroom, because it affects orientation towards the problem and to the process itself. To ensure that the task, in the form of a problem, is personally meaningful, pupils must be involved in the context of the problem. They must also be given significant decisions to make in order for them to create solutions (Murphy & McCormick, 1997). Affective and emotional factors also have to be taken into account throughout the process, since the difficulties that the pupils encounter may cause them approach the problems with a negative attitude, cognitive resignation, and even with some considerable anxiety and anguish that will hinder them and undermine their capacities (Freitas et al., 2004).

Problems in schools should emerge in novel situations, they must be close to the pupils' interests, open in form, and with a touch of intrigue or suspense which stimulate pupils to plan, make decisions, and put an effort into reaching their solution. According to Freitas et al. (2004), such problems could stimulate pupils to establish relationships between their prior knowledge and the knowledge required to solve the problem, as well as to make predictions and interpretations.

Levels of problem solving abilities

Problem-solving is strongly dependent on the existing context and pupils' emotions and attitudes which affect problem solving abilities. These abilities can be approached through a four-level model (Haapasalo 1998), in which a pupil's abilities and understanding related to problem solving are described via the role of the teacher (Table 1).

Table 1. The description of problem solving abilities (cf. Haapasalo, 1998).

Level	A pupil's abilities	A teacher's role
I	has no idea how to deal with the problem	shows how to solve the problem
II	understands the meaning of problem solving, orientates into familiar-like problems, and can make simple proposals in a group	supports problem solving
III	has a proper sense of problem solving and dares to apply new strategies	delivers problems
IV	can select the most appropriate strategy, sees variations and generalities, and shares them with others	facilitates problem solving

When orientating in problem solving, the pupil must first recognise the problem and then be interested and motivated to solve it (cf. Freitas et. al., 2004), factors which are affected by the complexity and familiarity of the problem together with the amount of information it includes (Taconis et al., 2001). Problem solving requires cognitive activities and strategies which need to be intertwined with domain knowledge. The roles of other people present in a classroom setting are also crucial factors in the problem solving process: i.e. pupil-pupil interactions and the teacher's non-exclusive roles of coach, facilitator or guide (Roth, 1995).

Different models of scientific inquiry in school science

Scientific inquiry generally refers to a process of asking questions and generating and pursuing strategies to investigate them. It is also a process of generating data, analysing and interpreting the data, drawing conclusions from it, communicating the conclusions, applying conclusions back to the original question, and perhaps following up on new questions that arise (Krajcik, Blumenfeld, Marx, Bass & Fredricks, 1998). Many scientific inquiry tasks given to pupils in schools do not, however, reflect the core attributes of authentic scientific reasoning. Many scientific inquiry tasks in school textbooks can be classified as simple inquiry tasks (Chinn & Malhotra, 2002), i.e. simple experiments, simple observations, or simple illustrations. It must also be emphasised here, that inquiry-based learning is not discovery learning, which is designed to lead students towards a predetermined view (Hodson & Hodson, 1998).

Instructional approaches have also been developed into school science that intend to depict the process of scientific inquiry. These models seem to include 4-5 similar phases. The first phase could be called "problem orientation" (cf. 'understanding the problem' Fisher, 2005; 'problem identification' Gott & Duggan, 1995; 'selection and articulation of the problem' and 'deciding upon variables' Aikenhead, 1989). In this phase the pupils recognise the problem, their knowledge base is activated and they formulate research question(s). The second phase could be labelled "strategic planning" (cf. 'planning the action' Fisher, 2005; 'planning the investigation' Gott & Duggan, 1995; 'creating hypotheses' and 'setting up an experiment' Aikenhead, 1989), in which the pupils set the hypotheses, plan and design the study. The third phase could be named "executing the study" (cf. 'tackling the task' Fisher, 2005; 'carrying out the investigation' Gott & Duggan, 1995; 'measuring variables' Aikenhead, 1989). This experimental phase includes creating sub-problems, defining variables, conducting measurements, recording data in tables and graphs, etc. The fourth phase, called "result analysis and evaluation" (cf. 'reviewing the situation' Fisher, 2005; 'interpreting the data and drawing conclusions' and 'evaluation of methods and results' Gott & Duggan, 1995; 'collecting, organising, graphing and interpreting data' in Aikenhead, 1989), consists of analysing the results and evaluation of the whole inquiry process. Finally, there could be the fifth phase like "communication" (cf. 'participating in scientific consensus making' Aikenhead, 1989), in which the pupils present their inquiry processes and results to the others.

The five-phase inquiry described above could be seen to fulfil the features of a problem solving process. The pupils should face a meaningful problem in a novel situation in order to satisfy their motivation towards orientation of problem solving. The situation should be open enough, but it must not overestimate the pupils' knowledge and skill bases which might cause them to be frustrated in planning, designing, or executing a purposeful study. The younger or more inexperienced the solvers are, or more challenging the problem is, the greater is the role of the facilitator, the teacher. Social interactions with peers are also important for solvers: either in their own study group or at the class level. The social environment in the classroom should have a positive atmosphere to enhance meaningful communication between the participants; e.g., the situation in which the pupils submit their results and the whole inquiry process is evaluated by their peers.

Methodology of Research

Research questions

Although several experimental studies have shown the effectiveness of a wide variety of teaching strategies for science problem solving in education (Taconis et al. 2001), only a few have paid attention to what a pupil actually does during a problem solving process. Furthermore, previous studies have mainly concentrated on problem solving with secondary and tertiary education pupils, so it is interesting to know about the problem solving processes of primary level pupils. This study concentrates on the pupils' own descriptions and explanations which are related to the different phases of the problem solving process: orientating towards the problem, planning and executing the solving process, evaluating and communicating the solutions. The research task is divided into two parts 1) What are the pupils' problem solving processes like? 2) What are the pupils' problem solving abilities in an open-ended scientific inquiry?

Context

The research data was collected in January 2005 in the context of three weekly 60–70 minute sessions in a voluntary science club in January 2005. Fourteen pupils focused on scientific inquiry, the aim of which was to construct the concept of density with the help of scientific experimentation. The four informants, who were 5th-graders, 11–12 years old, were paired in two groups. The problem solving process was based on open-ended inquiry that included five phases: orientation, planning, execution, evaluation, and communication.

The actual problem was contextualised in the orientation phase during the first session by three demonstrations: 1) one egg was floating (in a NaCl water solution) and the other had sunk (in water), 2) two similar-looking cubes (made of wood and aluminium) in water in which the one was floating and the other had sunk, 3) layers of syrup, water and olive oil in a glass. The demonstrations were used with the idea of creating an interesting situation from which a meaningful problem may arise which could then be solved. The goal for the pupils was two-fold: to explain the phenomena in each task and to say what the tasks had in common. In the same session the pupils were asked to plan how to solve the problem. They were given a sheet with the subtitles "research question", "preliminary hypothesis for tasks 1, 2, 3", "how to study", "what equipment and substances/materials are needed", "how to make notes", "how to present solutions", "how to evaluate the study". In the orientation phase, they were also offered large selections of both equipment and substances/materials, some of which were irrelevant to the task in hand.

In the beginning of the second session, the demonstrations were repeated, after which the pairs started to go ahead with their plans. They were asked to make notes about their actions, perceptions and results, then the pairs formulated their explanations about the tasks and the common feature of the phenomena. Extra equipment and materials were given to the pairs if they were necessary for the plan to be executed. The third session began with the pairs' own self-evaluation of their inquiry process. Each of the seven pairs then prepared a presentation of their study and finally they communicated their results and evaluation with the other pupils. The nature of the inquiry process was thus open-ended in its nature; the starting situation and the tasks were given, the equipment partly given, but methods and results were open (cf. Hegarty-Hazel, 1990).

Method

The present study is an exploratory case study by nature; this strategic choice fits in studying the phenomena that are tightly connected to its context (Yin, 1994). Both of the pairs were separately observed and video-taped during each of the sessions, and each of the pupils was individually interviewed after each session. All the interviews were based on video stimulation where the crucial parts of the problem solving sessions were reviewed step-by-step with the pupil (cf. Clarke, 2001). The data obtained consisted of transcriptions of the video-stimulated interviews (totalling 8 hours) and observation data checked from videotapes (5 hours).

Each of the three tasks performed by the pupil are analysed through the following dimensions: orientation and motivation towards solving the task; aims and actions during the execution of it, the roles of the pair and the teacher (see the grid in Appendix 1). The content analysis of both video and interview data is first made from pupil to pupil, and then the findings are combined in pairs to get the holistic picture of the pairs' processes. The content analysis of the pupils' performance and that of their own descriptions, give the answers to the first research question. Next, with the help of the problem solving ability model (cf. Table 1) each pupil's problem solving abilities are analysed in each tasks; the levels are summarised at the end of the analysis grid (cf. Appendix 1). The results of the problem solving abilities of the pupils give the answers to the second research question.

Results of Research

Problem solving processes

Pupils P1 and P2 worked together as a pair as did P3 and P4 also. Three of the pupils were keen on practising scientific inquiry, they were solution-orientated and their motivation levels were high in each of the three tasks (1 = the floating/sinking eggs in two liquids; 2 = the cubes floating/sinking in the same liquid; 3 = the layered liquids). Pupil P2 was not interested in solving tasks 1 and 3 and the motivation was low, but P2 was interested and highly motivated to solve task 2. In relation to the pupils' aims and plans in problem solving, it was typical that in each task, each pupil tried to imitate the demonstrations without variation. In the first task, however pupils P1, P3, and P4 were active in finding strategies to solve the problem, while P2 was not. In the second and third task, all the pupils were self-confident as to how to solve the problem – trying to repeat the demonstrations with the selected equipment and materials.

When the study plans were executed, there were differences concerning the pupils' actions. In tasks 1 and 3 the performance of pupil P1 was goal-orientated and constructive by nature. Pair P2 concentrated only on solving task 2, and P1 followed and trusted the pair's performance. Both pupils P3 and P4 were more intuitive and even playful when solving all the tasks; P3 also concentrated on drawing conclusions while executing the tasks.

The pupil-pupil interactions varied from rather passive participation (P2) to equal and shared responsibilities (P3 and P4). Pupil P1 relied on his own performance (except in task 2) and guided P2 in tasks 1 and 3. The teacher's role as a guide and supporter was notable with pair P1-P2, while hints and leading questions were enough for pair P3-P4. Pupil P2 needed most guidance and help from both the peer and the teacher. Instead, with a few hints offered by the teacher, P3 was able to find general solutions for all the tasks. This pupil was the only one who could draw conclusions from all the tasks and constructed the generally valid concept of density in order to explain them.

Problem solving abilities

In order to get a general view of each pupil's problem solving abilities, each dimension of performance was summarised for each pupil (P1–P4) in each of the tasks 1–3, and finally, the performance description of each pupil was combined together and reflected towards the problem solving abilities described in Table 1. The levels of the problem solving abilities of each pupil in solving each task are presented in Table 2.

Table 2. The problem solving ability levels of the pupils.

Pupil	Task 1	Task 2	Task 3
P1	II	II	II
P2	I	II	I
P3	III	III	III
P4	II	II	II

As can be noticed, the pupils differed from each other in their problem solving abilities (levels I–III), which indicates that even in the small cohort, there are pupils with varying abilities. Furthermore, each of them (except P2 in task 2) was on the same ability level regardless of the task, which validates the chosen ability model.

Discussions and Conclusions

Findings in this case study showed that the pupils were on quite a modest level when using strategic knowledge, which resulted in planning and execution phases in the open-ended inquiry process. The pupils concentrated on finding a procedural solution and they needed guidance to construct a generalised conceptual solution. Their procedural knowledge seemed to be still rather limited. One reason for this may be that the open-ended tasks were too challenging and the pupils did not have enough declarative knowledge. Declarative, strategic and procedural knowledge are intertwined (Taconis et. al., 2001) and this explains the pupils' low success in solving the tasks and constructing the concept of density in the open-ended inquiry. It is essential therefore, that pupils should be able to integrate and apply their existing knowledge, skills and strategies.

Motivation and interest, as well as cognitive and experiential background, were found to be significant for successful problem solving. Problem solving abilities are based on these individual features and background, and therefore in a classroom, there are pupils with different abilities; this is very important for teachers to take into account when they plan and lead problem solving in general. These abilities also vary according to the nature and structure of the problem to be solved. Scientific inquiry tasks offer possibilities for problem solving in the science classroom, but teachers must be aware of what properties are required of inquiry problems – familiarity, complexity, openness, the inclusion of information as well as the cognitive skills needed in the process.

The use of video stimulated interviews seems to be promising in taking the pupil's reflexive voice into account when describing and explaining the problem solving performance (cf. Clarke, 2001). As well as being a research method, it seems to be an efficient tool for teachers to develop reflexive thinking in their pupils and also one for pupils to use in problem solving – metacognitive awareness and skills are fundamentals in the expertise of problem solving.

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Appendix 1

The analysis grid of each pupil's problem solving performance in the given task, with a summary of his/her problem solving ability

The task (1-3):	Pupil 1	Pupil 2	Pupil 3	Pupil 4
Orientation (e.g., process-orientated – solution-orientated)				
Motivation (e.g., high – low; internal – external)				
Aim (e.g., finding new ways – repeating the demonstration)				
Performance (e.g., active – passive; planned – impulsive; creative – copying)				
Pair's role (e.g., interactive – passive; gives / needs support)				
Teacher's support (e.g., nature of support; amount of support)				
Ability level (I – IV)				

Adviced by Jari Lavonen, University of Helsinki, Finland

Kari Sormunen Professor at University of Joensuu, Finland.
P.O. Box 111, FIN – 80101, Joensuu, Finland.
Phone: + 358 13 251 2302.
E-mail: kari.sormunen@joensuu.fi
Website: http://www.joensuu.fi/englishindex.html