OPEN-ENDED INVESTIGATIONS IN SCIENCE: A CASE STUDY OF PRIMARY 6 PUPILS

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The purpose of this study was to find out (a) how pupils approach and carry out open-ended investigations, and (b) the difficulties that they face when carrying out such investigations. The study was conducted in a class of 39 primary six pupils of mixed ability who carried out four investigations. Data were based on pupil's questions, planning sheets and written reports, observations, field notes, and videotapes of pupils performing the investigations. The pupils were able to carry out the investigations with some success. However, their performance was hampered by the inability to identify prior conceptual knowledge relevant to the problem, a lack of planning, failure to control variables and repeat measurements, inadequate interpretation and presentation of findings, and little critical reflection and self-evaluation of their performance. Suggestions for helping teachers facilitate open-ended investigations are proposed, and implications for teaching are discussed.

In response to recent global reforms in education that emphasize inquiry and self-directed learning, the Ministry of Education in Singapore launched its vision of 'Thinking Schools, Learning Nation' in 1998. As part of this vision, the primary science syllabus (Ministry of Education, 2001) was also revised to incorporate more inquiry-oriented activities that focus on process skills such as interpreting data, controlling variables, formulating questions and hypotheses, and planning investigations.

Some practices, however, may impede the successful teaching of these skills. In a review of studies on science education in Singapore from 1971 to 1990, Toh (1993) found that students practised mainly low-order skills during laboratory activities. Chin, Goh, Chia, Lee and Soh (1994) found that for problem-solving activities in primary science, the question or problem was often posed by the teacher, and the solution often required only simple recall of specific information. On the other hand, problems that were posed by the pupils, that had no obvious or known answer, that required critique or analysis of a suggested solution, or that used tabular or graphical data were least often used. Teachers tended to choose direct and easily manageable exercises for their pupils, and to run smooth 'demonstration and verification' type of laboratory activities. A more recent study (Lee, Tan, Goh, Chia, and Chin, 2000) found that pupils either often or always followed detailed instructions to perform science activities or experiments. Pupils less frequently identified a researchable question or problem themselves, designed experiments with little or no assistance, or decided on the method used to solve a problem.

One way to provide pupils with laboratory activities that stimulate more thinking is to let them carry out open-ended investigations, where the holistic nature of scientific inquiry is emphasized (Woolnough, 1989). In such investigations, the practical skills are still upheld, but the links between the component skills are deemed equally important (Toh and Woolnough, 1990).

INVESTIGATIONS

Lock (1990) defined an investigation as 'an experimental study that requires first-hand pupil participation and leads towards providing evidence that permits a question, posed at the outset, to be answered.' He categorised the nature of investigations by describing them in relation to two intersecting axes, one representing the continuum between closed-ended and open-ended investigations, and the other continuum between teacher-directed and pupil-directed approaches. Open-endedness refers to whether more than one design, solution, or answer is possible. It can also refer to whether the problem and method are defined or undefined for the student. The above author identified five key questions in relation to enhancing the open-endedness of practical work, all of which ask whether it is the student or the teacher who has control over specific elements involved in the work. These include: (a) Who defines the area of interest? (b) Who states the problem? (c) Who does the planning? (d) Who decides on the strategy used? and (e) Who interprets the results?

Duggan and Gott (1995) see an investigation as a kind of problem-solving for which there is no routine method of arriving at a solution. According to them, 'Investigations are not about isolated skills or process, nor are they about concept formation or discovery. They are, however, about using and developing skills, concepts and procedural understanding in finding the solution to a problem' (p. 144). The cognitive processes needed to solve problems involve an interaction of conceptual and procedural understanding. Conceptual understanding is the 'understanding of the ideas in science which are based on facts, laws and principles and which are sometimes referred to as "substantive" or "declarative" concepts' (Gott & Duggan, 1995, p. 26).

Procedural understanding, on the other hand, refers to the 'ability of pupils to put together a solution to a practical problem from their own resources of skills and concepts rather than following a recipe from a worksheet or teacher' (Duggan & Gott, 1995, p. 139). Gott and Duggan (1995) coined the term, 'concepts of evidence' to refer to the concepts that are associated with procedural understanding, and structured them around the four main steps of investigative work, (viz. design of the task, measurement, data handling, and evaluation of the complete task). For example, the concepts of evidence associated with design are variable identification, fair test, sample size, and types of variables. Those pertaining to measurement include relative scale, range and interval, choice of instrument, repeatability, and accuracy. Concepts related to data handling are the appropriate use of tables, graph types, noticing patterns, and dealing with multivariate data. Finally, concepts relevant to evaluation of the task include the reliability and validity of the ensuing evidence.

Since whole investigations can provide pupils with the opportunity to investigate problems of particular relevance to them, they encourage ownership while also engaging the integrated processes which are commonly found to be most difficult to learn (Arena, 1996). They 'allow pupils to synthesise their skills, processes and understanding into an overall strategy' and by virtue of their holistic nature, 'make them a unique and invaluable tool in the practical science classroom' (Duggan & Gott, 1995, p. 146).

STUDIES OF HOW PUPILS CARRIED OUT PRACTICAL INVESTIGATIONS

In a study of pupils performing practical tasks carried out by the Assessment of Performance Unit in the UK, Harlen, Black, and Johnson (1981) found out that very few 11-year old pupils repeated observations or measurements as routine, or made notes in the course of an investigation other than recording measurements. Pupils' difficulties with identifying, controlling, and manipulating appropriate variables have also been documented by Donnelly (1987) and Duggan, Johnson, and Gott (1996).

Gott and Duggan (1995), when summarising the findings of the National Curriculum Council (NCC) project, reported that: (a) pupils' performance improved with age, (b) pupils performed better in investigations set in scientific contexts than in 'everyday' contexts, (c) open contexts were more difficult than closed ones, (d) motivation of pupils doing the investigations was high, (e) children experienced difficulty in identifying independent variables as continuous, where appropriate, and (f) when the number of independent variables was more than one, there was an increase in relevant control variables being ignored or overlooked. Pupils found investigations dealing with multiple and continuous variables more difficult than those involving single, categorical variables.

Hackling and Garnett (1995) found that the most notable weakness of pupils' investigation skills was their lack of problem analysis and planning. Very few pupils planned how they would measure variables or record data before they commenced data-collection procedures. In organising and interpreting their information, pupils frequently made interpretations based on inadequate control of variables. They also demonstrated little awareness of the methodological weakness of their experiments.

Watson's (1994) study of 11- and 12-year old pupils found that some less successful pupils arrived at a solution to the problem without even interpreting the results obtained, and others started planning without even reformulating the problem. These pupils seemed to be working on the activity without purpose and carrying out the experiment in a mechanical, unthinking way for a significant part of the time. Watson (1994) inferred that the lack of discussion about the problem led to a lack of shared purpose, and to some pupils within the group taking little part in formulating the strategic plans to solve the problem. He suggested that teachers structure the lesson so as to explicitly give time for pupils to think about the problem, reformulate the problem, plan, interpret results, and evaluate them, as well as to analyse the problems given to the pupils in order to predict possible difficulties for them.

Key's (1998) study of Grade 6 pupils who generated their own questions for investigations found that pupils who designed descriptive investigations were able to avoid difficulties of confounding variables. Of the pupils who designed experimental investigations, the ones dealing with one independent variable generally could carry out their investigations without problems. However, the pupils who manipulated several variables encountered difficulty in interpreting the meaning of all their experimental trials.

Studies carried out in the local context on open-ended investigations by Toh and Woolnough (1993) and Toh, Boo, and Yeo (1997) found that pupils provided with explicit knowledge (i.e. specifically taught the strategies in connection with planning, measurement, procedures, and communication) performed significantly better in overall achievement on such investigations than those using only tacit knowledge and who were not provided with pre-training. The performance of the pupils provided with explicit knowledge improved for the skills of planning and communicating, but not for performing and interpreting. Toh and Woolnough (1993) thus believed that teachers who want to teach open-ended laboratory investigations should emphasize skills such as planning and communicating.

BACKGROUND TO THE PROBLEM AND PURPOSE OF THE STUDY

In much of the conventional science practical activities carried out by primary school pupils in Singapore, the pupils are guided most of the way, from being provided with the aim of the investigation to getting help in writing the conclusion. However, with the current emphasis on thinking skills in the revised science curriculum (Ministry of Education, 2001), the role of open-ended investigations has become increasingly important. Pupils are encouraged to take more responsibility for the conduct of their own investigations. This move towards investigative work represents a significant change in emphasis in the nature of practical work in primary science. With the implementation of the revised curriculum, the focus is on innovative and creative thinking, lifelong learning, and the ability to work in teams. Open-ended investigations provide an excellent means to achieving these goals as they provide plenty of opportunities for pupils to develop inquiring minds and problem-solving skills.

The purpose of this study is to find out how Primary 6 pupils perform in open-ended investigations. The research questions are:

1. How do the pupils approach and carry out open-ended investigations?
2. What are some difficulties that pupils encounter when carrying out such investigations?

METHOD

The study was conducted in a Primary 6 class (aged 11 to 12 years) of 39 pupils of mixed-ability. The second author was the science teacher. During the open-ended investigations for this study, the pupils worked in eight same-sex groups of four or five formed by themselves. The pupils were informed that they would be carrying out four investigations that were different from the ones that they were used to, in that they would be given more autonomy in designing and conducting the investigations compared to the relatively more structured activities typically found in their science activity book.

Prior to carrying out these investigations, the pupils were taught the importance of proper planning in designing an investigation such as keeping certain variables constant to ensure a fair test. Examples of investigation, such as which soil type (garden, sand or clay) would be best for the growth of green beans, were given. Each of the four investigations lasted about 2.5 hours over three sessions. The pupils were provided with planning sheets containing questions which were designed to help them focus on the task at hand and to engage actively in thinking about what they were doing.

Examples of questions found in the planning sheet were: (a) What is the problem that you are investigating? (b) What do you know about this which might be useful? (c) What do you think might happen in your investigation? and (d) Why do you think this might happen?

These questions served as scaffolding tools and guide pupils to define the problem, tap on related prior knowledge, predict outcomes, and explain respectively. The planning sheet also contained spaces for the pupils to write down their experimental design, procedure, results, and conclusions. To help them reflect on the overall conduct of the activity after they had finished their investigation, the students were asked what changes they would make if they were to repeat the experiment, what further questions they had, and what were some of the problems they faced while carrying out the investigations.

The problems for the four investigations were:

1. Which type of paper is most absorbent?
2. Which material is best for keeping water hot?
3. Which type of soap solution will give bubbles which last the longest?
4. Which material can keep cool water at the lowest temperature?

The first two investigative questions were given by the teacher but the last two investigations were based on pupil-generated questions, selected from a list submitted by the pupils. For all the four investigations, the pupils did the planning, decided upon the strategy to be used, and interpreted the results themselves.

As the purpose of this study was to assess pupils' ability to carry out open-ended investigations independently, the teacher did not give explicit instructions and intervened only minimally. Although pupils worked in groups, they had to hand in separate reports. Four groups of pupils were videotaped while carrying out their investigations—two 'good' groups (groups 4 and 5) and two 'weak' groups (groups 2 and 3). They were chosen to obtain information on both the better and the weaker pupils. Field notes were also taken.

Data from the following multiple sources were analysed in relation to each other: (a) planning sheets and written reports, (b) observation field notes, and (c) video tapes. Pupils' responses on the planning sheets were used as primary data sources. Observation field notes, transcripts from relevant parts of the discourse of the four groups which were videotaped, and descriptive notes taken during the viewing of the videotapes were then used as secondary data sources, to provide a context for the interpretation of the data.

RESULTS

Investigation 1: Which Type of Paper is Most Absorbent?

The problem was not directly based on textbook knowledge but the pupils seemed hesitant to write down anything that they might have learnt from everyday experiences or observation. Only 45% of pupils' responses were predictions relevant to the task at hand. Irrelevant statements included 'We will be wasting water since we have to try to repeat the steps with different papers.'

All the groups controlled the amount of water to test for water absorbency. The groups used different types of papers, ranging from as few as three to as many as eight. These included tissue paper, toilet paper, kitchen towel, writing paper, drawing paper, construction paper, tracing paper and cardboard. Seven groups controlled the area of the paper and one group (group 6) controlled the thickness of the paper. The latter group did this by using a number of layers of the thinner papers to equal the thicker ones. None of the groups controlled the mass or weight of the various papers used.

Basically, the groups used four methods to carry out the investigation. Groups 2, 6 and 8 used the first method. They put the whole piece of paper into a tray and poured water into one corner of the tray. The time taken for the whole sheet to get wet was then recorded. For this method, the groups stopped timing when the water spread throughout the paper until all of it was wet. Groups 3 and 4 also poured water into trays containing the different papers but they waited until the papers were totally wet and then measured the remaining unabsorbed water by pouring it into a measuring cylinder. They then found out the amount of water absorbed by the individual papers by subtracting the amount of unabsorbed water from the initial amount. In addition, groups 3 also took the time taken for each paper to get wet.

Groups 1 and 5 soaked their choices of papers in water and then squeezed the papers to collect the water absorbed. The paper from which the most water was collected was deemed the most absorbent one. Both groups did not take into account the problem of water lost due to spillage or the different papers not being squeezed to the same extent. Group 7 filled a tray of water. They then dipped one end of the papers into the water and recorded the time taken for the water to travel to the other end. This method resembles the process of chromatography.

Table 1 shows samples (actual versions of the original) of three ways in which the pupils presented their results and wrote their conclusions. Two groups merely stated their results using abbreviated statements. Group 1 compared the amount of water absorbed by the different papers. However, they did not indicate what the recorded volumes meant, or use headings to organise their information. Group 7 just listed the papers from first to sixth positions, without explaining how this order was made. Even though this group had used the time taken for water to travel up the paper as a dependent variable, no such data were recorded. Five groups made use of tables to record their results. For example, group 2 compared the time taken by the different type of papers to get fully wet.

Table 1
Samples of Students' Records for Investigation 1

Group	Results			Conclusion
1	Kitchen towel - 18 ml Construction paper - 10 ml Tissue paper - 16 ml Writing paper - 5 ml Drawing paper - 3 ml			The kitchen towel is the most absorbent.
2	Type of paper	Time taken for paper to absorb the water	Amount of water poured	Thinner paper takes shorter time to absorb the water.
	Construction paper	50 s	200 ml	
	Drawing block	3 min. 54 s	200 ml	
	Coloured paper	1 min.	200 ml	
	Tracing paper	1 min. 32 s	200 ml	
	Kitchen towel	1 s	200 ml	
	Tissue paper	2 s	200 ml	
	Writing paper	1 min. 59 s	200 ml	
7	1st : Tissue 2nd : Kitchen Towel 3rd : Tracing paper 4th : Cardboard 5th : Typing Paper 6th : Construction Paper			The paper which is the most absorbent is the tissue paper.

Only group 6 repeated the investigation for each type of paper and then found the average result. All the other groups carried out the investigation only once for each type of paper. All the groups, except group 2, based their conclusions on their findings and chose one of the types of paper that they used as the most absorbent paper. Group 2's results indicated that kitchen towel was the most absorbent but their conclusion was 'thinner paper takes shorter time to absorb the water.' This group either totally disregarded their results or did not know how to interpret them as they made a conclusion that was not based on their findings.

In response to the question 'If you were to repeat the experiment, what changes would you make?,' the pupils' answers pertained mainly to changing the properties related to the materials used (e.g. changing the amount of water used, the size of paper, the thickness of the paper, and using other types of paper) rather than suggestions to improve the design or methods.

Pupils' questions about the topic focused mainly on the procedure and materials used (e.g. 'How much water must I use?,' What is the size of paper [that I should use]?,' and 'How any types of paper to use?.' Questions pertaining to the implications of the results and the conclusions (e.g. 'Why is it that the drawing block took the longest time to absorb the water, even longer than cardboard?') were rare. The abundance of procedural questions and lack of 'wonderment' questions that focus on explanations, cause-effect relationships, predictions, anomalies, applications, strategy, and that indicate deeper thinking (Chin & Brown, 2000), could be due to pupils' lack of conceptual knowledge, inability to think more deeply, or their reluctance or inability to express themselves in words.

Problems faced by the pupils included not knowing 'how to start' and 'how to find the amount of water absorbed.' The pupils also found pitfalls in the hands-on stage which they did not anticipate in the planning stage (e.g. how to actually measure the water absorbed by the different papers and what apparatus they would use). Although the pupils drafted rough plans, there was little thought given to how to specifically put their plans into action.

Investigation 2: Which Material is Best for Keeping Water Hot?

Pupils were to select a material that would be most suitable to be wrapped around a beaker of hot water to keep it hot for the longest time. Pupils writing about their prior knowledge gave an insight into their misconceptions about heat and metals: 'Materials like metals are the best for keeping water hot' and 'Paper, tissue, and cardboard are not effective.' These pupils thought that since metals are good conductors of heat and get hot fast, they should also be better than other materials in keeping water hot.

All groups used aluminium foil as one of the materials to be tested. The other types of materials used varied across the groups, and included cloth (towel), writing paper, toilet paper, tissue paper, paper bag, and plastic bag. Group 6 members were the only ones who controlled the thickness of the various materials by repeatedly folding the materials until they reached a thickness of 2 mm. All the groups, surprisingly, had similar experimental procedures. The steps involved were: (a) take the initial temperature of the hot water, (b) wrap the material around the beaker of hot water, (c) take the temperature of the water again after a specified time, and (d) find the difference between the beginning and the final temperatures.

The time interval used ranged from one to three minutes. This choice of time interval, however, was too short to allow a significant temperature decrease and ensure accuracy in their results. All groups took only one other reading after the initial one. Only groups 4 and 5 took repeated measurements. Several pupils did not use proper techniques when handling the thermometer. Instead of holding the thermometer at its top end, some held its stem. A few pupils lifted the thermometer out of the water into the air when taking their readings, and this would have resulted in a lower temperature reading. Such mistakes would have led the pupils to arrive at erroneous conclusions.

Samples of how the results were recorded and conclusions were given are shown in Table 2. Group 1 wrote down the four materials used and next to each, a temperature reading. There was no indication of what temperature readings they were (initial, final or the difference between the two). There was also no mention of initial temperature and whether it was controlled for. The temperature reading recorded next to aluminium foil was the highest and the group's conclusion was that aluminium foil was the best for keeping water hot.

Table 2
Samples of Students' Records for Investigation 2

<table>
<tr><th>Group</th><th>Record of Results</th><th>Conclusion</th></tr>
<tr><td>1</td><td>Cloth: 50°C
Aluminium foil: 76°C
Toilet paper: 50°C
Foolscap paper: 66°C
(Note: No mention of initial temperature and pupils were observed not to have controlled it).</td><td>Aluminium foil is the best for keeping water hot.</td></tr>
<tr><td>3</td><td>Beginning Temperature = 79°C
<table>
<tr><th>Temp.</th><th>Aluminium foil</th><th>Cloth</th><th>Plastic bag</th><th>Paper bag</th></tr>
<tr><td>Final temp.</td><td>73°C</td><td>67°C</td><td>62°C</td><td>67°C</td></tr>
<tr><td>Decrease temp.</td><td>6°C</td><td>12°C</td><td>17°C</td><td>12°C</td></tr>
</table></td><td>As we change the temperature of water, the level of the thermometer increases.</td></tr>
<tr><td>5</td><td>
<table>
<tr><th>No.</th><th>Material</th><th colspan="3">1st try</th><th colspan="4">2nd try</th></tr>
<tr><th></th><th></th><th>Initial temp.</th><th>Final temp.</th><th>Diff.</th><th>Initial temp.</th><th>Final temp.</th><th>Diff.</th><th>Ave. Diff.</th></tr>
<tr><td>1</td><td>A4 paper</td><td>76°C</td><td>64°C</td><td>12°C</td><td>76°C</td><td>68°C</td><td>8°C</td><td>10°C</td></tr>
<tr><td>2</td><td>Alum. Foil</td><td>76°C</td><td>71°C</td><td>5°C</td><td>76°C</td><td>68°C</td><td>8°C</td><td>6.5°C</td></tr>
<tr><td>3</td><td>Cloth</td><td>76°C</td><td>69°C</td><td>7°C</td><td>76°C</td><td>71°C</td><td>5°C</td><td>6°C</td></tr>
</table></td><td>Cloth can keep the water hottest.</td></tr>
</table>

Groups 3 and 5, on the other hand, presented their data in tables, using labelled headings, and clearly indicating the initial and final temperature readings and the difference between the two. However, the difference in temperature obtained for aluminium and plastic bag by group 3 do not seem to match the respective materials and look as though they should be reversed. The same can be said for the readings obtained for aluminium and A4 paper by group 5. This suggests inaccuracy in the recording of their results. Furthermore, group 3's results indicated that aluminium was the best material for keeping water hot (a dubious finding) but they gave a conclusion ('As we change the temperature of water, the level of the thermometer increases') that was not based on their results. These pupils had difficulty in interpreting their results. Three groups concluded that aluminium was the best material, which is incorrect. This could be due to their not having controlled the initial temperature of water, or not using the thermometer properly. Alternatively, the pupils might have felt compelled to ignore or fudge their data and adjust their results to match their prediction of aluminium foil being the best in keeping water hot.

As in investigation 1, the pupils mainly suggested that if they were to repeat the experiment, they would make changes in the materials used (e.g. thickness, number of types) rather than modifications in their experimental designs. Suggested improvements such as one beaker could have been left with no insulation to be used as a control, or that a lid could be put on each beaker to reduce evaporation, were not given. Students' questions like 'How much water to use?' show a preoccupation with the procedural aspects of the investigation. 'Why the temperature of hot water must be the same?' indicates that the pupil did not understand the concept of experimental control and a fair test, while 'Why do different materials keep the water hot for different times?' seems to be seeking explanations of an observed phenomenon. Questions of the type, 'Besides the method that we used, what other methods can we use to do this experiment?' reflect divergent thinking.

Investigation 3: Which Type of Soap Solution Will Give Bubbles Which Last the Longest?

Only half the class was able to make predictions relevant to the purpose of their investigation (e.g. 'The less the amount of water added, the bubbles will last longer because there is more soap' and 'Shampoo will produce the bubble which will last the longest because shampoo produces the most foam'). The rest gave irrelevant statements (e.g. 'The bubbles will not last because of the wind blowing').

The pupils brought their own soap solutions for this experiment and were supplied with copper wires which they bent into a circular loop to blow the bubbles. Groups 1, 2, 3 and 8 did not control the way they blew the bubbles each time. Groups 4, 5, 6 and 7, on the other hand, appointed a 'bubble blower' who blew the bubbles in the same manner for each try. The groups started timing the life span of the bubbles from the moment it was fully formed to the time it burst of its own accord. Bubbles that burst due to knocking into someone or something were not counted. The pupils used two methods to carry out their investigations. Some groups maintained the same proportion of water and soap but varied the type of soap used, for example, hand soap, washing detergent and shampoo. Others used the same type of soap throughout the investigation, but varied the strength of the soap solution by varying the amount of soap used.

Samples of the ways in which pupils presented their results and conclusions are shown in Table 3. Group 1 measured their amounts of detergent in spoonfuls whereas the other groups used a more precise measure, in millilitres. They did not indicate how much water they added to the detergent, and also did not use headings to label their data. Groups 1 and 2 arrived at contrasting findings, even though both groups used one detergent and made solutions of varying strengths. This was probably due to the different ranges in concentration used. Only groups 4 and 6 took each reading three times and then found the average. The others, however, took only one reading for each solution. All groups, except group 8, were able to interpret their results and arrived at conclusions based on their findings which answered the investigative question. Examples included 'The more water, the longer the bubbles lasted' and 'Body foam produces the bubbles that can last the longest.'

Table 3
Samples of Students' Records for Investigation 3

Group	Record of Results				Conclusions
1		3 spoons detergent 8s	2 spoons 6 s	1 spoon 4 s	The thicker the detergent, the longer it lasts.
2		Amount of water water	Amount of detergent	Time	The more water added, the longer the bubbles will last.
		100 ml	50 ml	8 s	
		150 ml	50 ml	13 s	
		200 ml	50 ml	16 s	
4	Try	Soap (50 ml)	Shampoo (50 ml)	Detergent (50 ml)	I think that we could use soap solutions to play bubbles as it lasts the longest.
	1st	32.5 s	5.5 s	13 s	
	2nd	45.5 s	9.5 s	18 s	
	3rd	36.5 s	3.5 s	17 s	
	Ave.	38 s	6 s	16 s	

On what changes they would make if they were to repeat the experiment, pupils who used only one type of soap in varying concentrations wanted to experiment with other types of soap. A few others suggested using a larger column of water and detergent, as the small amount of soap mixture they had used was too little to allow the wire loop to be completely immersed in it. Questions that pupils asked included 'How many scoops of soap solution and water must I use?,' and 'What shape should the wire be bent into?' The latter question suggests some pupils could have been nursing the misconception that different shapes of loops would give rise to different shapes of bubbles!

Common problems related to the bubbles bursting before they could be completely formed, or bubbles knocking onto something and bursting. Other problems included not knowing how hard to blow the bubbles and how to measure the life span of bubbles, being unable to 'keep the bubble size the same,' and finding it difficult to follow the bubbles around as they kept floating away. For the latter problem, one pupil from group 6 solved this by catching the bubble with the loop so that the bubble sat on the loop. This made for easy timing of the life span of the bubble and also reduced the chances of the bubble having an accidental death. Other groups that faced the same problem soon copied this innovative idea. This seemed to be the norm rather than the exception: pupils, instead of trying solve problems on their own, copied from successful ones who had already found solutions to their problems.

Investigation 4: Which Material Can Keep Cool Water at the Lowest Temperature?

This investigative problem was similar to investigation 2. All the groups used cloth. Other materials used were aluminium foil and various kinds of paper (writing paper, tissue paper, newspaper, and kitchen towel). Only group 7 brought two different materials, rubber mat and corrugated cardboard. All the eight groups used a similar experimental design. The basic steps included: (a) put an amount of cold water into the beaker, (b) measure the initial temperature of the cold water, (c) use the different materials to cover the beaker, and (d) measure the temperature of the water after a certain period of time. The only difference lay in where the material was wrapped and the time interval between the initial and the final temperature readings. More than half the class wrapped the side of the beaker with the different materials. Group 5 and 6 wrapped the top of the beaker as they thought that more heat would be taken in by the cold water through direct contact with the air above than through the side of the beaker. Only one group (group 4) wrapped the whole beaker completely.

As in investigation 2, common weaknesses included not controlling the thickness of the various materials, using too short a time interval (<1 min) that was insufficient to register an appreciable temperature difference, and not taking repeated measurements and finding the average. Samples of students' records of their results and conclusions are given in Table 4.

Table 4

Samples of Students' Records for Investigation 4

<table>
<tr><th rowspan="3">Group</th><th rowspan="3">Time interval between initial and final readings</th><th colspan="5">Record of Results</th><th rowspan="3">Conclusion</th></tr>
<tr><th colspan="5"></th></tr>
<tr><th colspan="5"></th></tr>
<tr><td>3</td><td>1 minute</td><td colspan="5">Temperature of ice water=6°C in 1 min.
Temperature of ice water with A1 foil = 7.5°C in 1 min.
Temperature of cloth with ice water = 8°C in 1 min.
Temperature of ice water with writing paper = 8.5°C in 1 min.
Temperature of ice water with newspaper = 8.5°C
Temperature of ice water not kept constant).</td><td>We find out that the best material to keep water cold is aluminium foil.</td></tr>
<tr><td rowspan="6">5</td><td rowspan="6">5 minutes</td><td rowspan="2">Material</td><td rowspan="2">Initial Temp °C</td><td colspan="3">Temp. after 5 minutes (°C)</td><td rowspan="6">The cloth can keep the water hottest.</td></tr>
<tr><td>1st try</td><td>2nd try</td><td>Ave.</td></tr>
<tr><td>Tissue</td><td>8</td><td>13</td><td>12</td><td>12.5</td></tr>
<tr><td>Cloth</td><td>8</td><td>9</td><td>10</td><td>9.5</td></tr>
<tr><td>Al. Foil</td><td>8</td><td>11</td><td>10</td><td>10.5</td></tr>
<tr><td>News-paper</td><td>8</td><td>15</td><td>9</td><td>12</td></tr>
<tr><td>8</td><td>15 seconds</td><td colspan="5">1st try = (blank) = 9°C (15 s / 200 ml)
2nd try = (cloth) = 12°C (15 s / 200 ml)
3rd try = (al. foil) = 14°C (15 s / 200 ml)</td><td>(No conclusion was written).</td></tr>
</table>

Group 3 pupils recorded their results using short sentences instead of labelled headings, and the wordiness made it difficult to grasp the information holistically at a glance. As with group 3, Group 8's record of temperature readings gave no indication of whether they were the initial or final readings or the difference between the two. Group 5's record of results were relatively more detailed and comprehensive. Group 3's dubious conclusion of aluminium being the best material in keeping water cool, could have stemmed from the group's failure to use a sufficiently long time interval between the initial and the final temperature readings, or their not keeping the initial temperature of ice water the same for all materials tested.

When asked what changes they would make if they were to repeat the experiment, several pupils responded that they would change the 'materials used,' 'initial temperature of the water,' 'amount of water,' 'size of beaker' and 'place where the experiment was carried out.' These are not variables that would critically change the set-up or the results of the investigation. The pupils did not suggest improvements such as having a longer time interval between initial and final readings, or making changes in the way they wrapped the material around the beaker, for example, from just around the beaker to completely covering it, including the top. Changes that would significantly improve the design, and consequently the accuracy of their results, were hardly mentioned.

Pupils' questions included further investigatable questions such as 'Since cloth was the best, I want to know among different types of cloth, which is the best?' and procedural questions (e.g. 'How long must we wait before measuring the temperature of the water?'). Common problems related to having to make their own decisions regarding the procedural aspects of an investigation (e.g. not knowing 'what initial temperature to start with' or 'how thick the material must be'), making sure that the initial temperature was the same for all the materials used, and difficulties with measuring the thickness of the material and reading the thermometer.

DISCUSSION

Limitations of the Study

There were two main limitations in this study. First, the participants of this study were all from one class. Thus, the above findings from this small sample may not be generalisable across all settings. However, the detailed description and analysis of this case study class, which displayed a range of academic abilities, allowed us to study pupils' performance in more depth than would have possible if we had only looked at the scores of a large sample. Second, only four open-ended investigations were carried out over a short period of time. The limited curriculum time did not allow for the conduct of more such investigations as they were time-consuming in nature. If time had permitted, the pupils could have carried out more investigations of a wider range of types, over a larger number of concept areas and a longer period of time, as this could have provided more information about their performance.

Pupils' Performance on the Open-ended Investigations

The pupils had difficulty identifying knowledge that was relevant to the problem at hand. For investigations 2 and 4 where it was necessary for them to tap into their knowledge of good and bad conductors, many pupils found it difficult to apply the theoretical knowledge they had learnt from the textbook to practical use in the investigative tasks. For investigations 1 and 3 which involved more real-life experience than textbook knowledge, several pupils did not invoke much of their personal experiences about water absorbency and soap bubbles. This could be due to their belief that what is found in the books have more value than knowledge gained from daily life experiences or personal observation. Thus, this knowledge remained inert. The above findings suggest that before pupils actually carry out their investigations, teachers could elicit their prior conceptions first and help them identify ideas that would be relevant and useful to the investigation.

Pupils' writing about their prior knowledge and prediction of outcomes revealed their preconceptions and misconceptions, such as metal or aluminium foil is best for keeping water hot as it is a good conductor of heat. Some of the pupils believed so staunchly in this idea that it led them not only to make wrong predictions, but also to arrive at incorrect results and conclusions, despite experimental findings that showed otherwise.

Some groups did not give much thought to details about the investigations, jumped right in, and were naive in thinking that their plans would be foolproof. However, after putting their sketchy plans into action, they were confronted by many unforeseen problems. When faced with problems, these pupils were stuck and resorted to asking the teacher for assistance, changing their plans during the investigations, imitating what the more successful groups did, or simply ignoring the problem. Some groups even decided on the materials requirements first before working out their plan, without knowing how these materials would be used in the actual procedures. A few pupils (group 7) plunged straight into experimenting without even drawing up a plan for investigations 3 and 4. Therefore, teachers need to emphasize the importance of drawing up a detailed plan and anticipating potential problems for the successful completion of open-ended investigations.

For investigations that had some similarities to those given in the science activity book (viz. investigations 2 and 4), the various groups came out with designs and procedures that were almost identical. However, for investigations 1 and 3, which were more unfamiliar and set in everyday contexts, multiple designs and methods were used. There were four different approaches taken by the eight groups for investigations 1, and two for investigation 3. This suggests that if the investigation topic is reminiscent of 'school science,' the pupils might perceive it as a routine science investigation and this can limit free play of ideas and constrain pupils to 'think within the box.' However, if the topic is not directly related to the school science syllabus, the pupils seem to exhibit more creative thinking. One implication is that after using 'starter investigations' set in more familiar school science contexts, teachers can set investigations in more novel, yet everyday contexts, to encourage creative thinking in pupils.

With the exception of group 6, most groups had some difficulty with controlling the relevant variables to make the investigation a fair test. Thus, pupils need a lot of practice in identifying variables and also, the need to control them has to be emphasized. Several groups (except groups 4, 5, and 6) took measurements only once for each sample instead of two or three times to find an average, despite having been taught this previously. It appears that the pupils had only been following the teachers' instructions blindly, and had not internalised this concept nor understood the rationale and significance of doing this. The pupils were eager to finish the investigations as soon as possible and tried to cut down on certain procedures, such as taking the minimum number of measurements or using a shorter time interval without realising the impact on the reliability and validity of the results obtained.

The study by Lubben and Millan (1996) revealed that some students aged 11 to 16 viewed repeated measurements as a waste of resource materials and time, as confirmation, as science routines, or a process of becoming familiar with equipment. Coelho and Séré (1998) found that most 14 - to 17-year-olds believed in the existence of a 'true value' and did not accept the idea of measurement spread. That students do not really understand the need to take repeated measurements was also reported by Séré, Journeaux, and Larcher (1993), who found that even among first-year university students, 'the general view is that, the more measurements one makes, the "better" the result is, without understanding the nature of this "better" (p. 427).

Many of the activities found in the prescribed primary science activity books guide the pupils closely in carrying out the investigations. A few of the activities in these books even indicate the number of readings the pupils must take by having the 'results table' drawn for them. Workbook authors should design curriculum materials that are more challenging and open-ended and that require pupils to think about how best to present their findings. Teachers could also work around this problem by modifying the workbook activities instead of following them closely.

In presenting their findings, most groups typically used tables to display their results, which was appropriate and adequate in all the four investigations as they all involved a single, categoric, independent variable. Although a bar chart could have been used as a form of visual representation, it serves only as a display, so was not essential for the purpose of interpretation. In cases where pupils experimented with different amounts of detergent in investigation 3, a line graph would have been appropriate as a continuous variable was involved. The pupils were able to indicate the units of measurement correctly. However, as can be seen from Tables 1 to 4, common problems in pupils' presentation of results included omitting labelled organizing headings and not indicating what the numerical data represented (e.g. Table 2, Group 1), indicating the units of measurement repeatedly throughout the table for every reading instead of only once at the top in the column heading (e.g. Table 3, Group 2), and using too many unnecessary words to record the data (Table 4, Group 3). For the latter problem, the ability to represent the raw data more succinctly would have facilitated 'eye-balling' the data to interpret trends and patterns more holistically.

Some pupils had difficulty in interpreting the data and making relevant conclusions based on the results obtained; their conclusions had little or no connection with the question posed in the problem (e.g. group 3 for investigation 2 in Table 2). In some cases, the interpretations or conclusions made did not follow the findings, possibly because of the influence of strongly entrenched, biased preconceptions (e.g. aluminium foil is the best for keeping water hot). An implication of these findings is that teachers should impress upon their pupils that the conclusions that they make should not only answer the original question in the problem, but should also be consistent with and arise from the data obtained. Work by other researchers (Doran, Fraser, Giddings, & De Ture 1995; De Ture, Fraser, & Doran 1995) have found that students find formulating conclusions to be relatively more difficult than performing the investigation. Also, the study by Germann and Aram (1996) revealed that many pupils did not attend to their hypotheses or provide specific evidence when drawing their conclusions.

When asked what changes they would make if they were to repeat the investigation, most pupils gave responses that mainly focused on the superficial or practical aspects of the investigational procedures or the materials used. Several had the naive notion that simply changing the materials used would lead to an improvement in experimental design. Having to think about suggestions for improvement allowed some pupils to reflect critically on what they had done, but not many gave suggestions on how to improve their design of the investigations or the methods employed.

In response to what questions they had with regard to the investigation, most of the pupil's questions focused on investigational procedures and materials used. Questions on the implications of the results and the conclusions were rare. Since the ability to ask a variety of 'good' questions is essential to scientific inquiry and meaningful learning, pupils can be made aware of the various types of higher-level questions beyond the procedural kinds, which can stimulate more productive thinking. Pupils' questions can also provide valuable information for the teacher about pupils' puzzlement, wonderment, and what they want to know.

CONCLUSION

Although the pupils were able to complete all the four investigations with some success, their performance was hampered by weaknesses associated with the identification of prior conceptual knowledge relevant to the problem, lack of planning, failure to control variables and repeat measurements, inadequate interpretation and presentation of finds, and little critical reflection and evaluation of their own performance. A critical component of pupils' ability to succeed on open investigative tasks is conceptual knowledge as well as procedural knowledge.

Most students will not learn skills and processes in passing, and these skills should be taught overtly (Tamir, 1989). Until some of the skills required for conducting investigations are explicitly taught, pupils' performance is unlikely to improve. In teaching about investigations, the teacher needs to explicitly introduce concepts related to design (variable identification, control of variables, fair test), measurement (relative scale, range and interval, repeated trails), data handling (use of tables, interpretation of data), and evaluation (reliability and validity of evidence). Pupils also need practice in applying these concepts over several investigations.

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