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Facilitating Science Investigations: Some Suggestions for the Teacher

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Abstract

Students encounter a number of difficulties when carrying out science investigations. These include activating relevant prior knowledge, planning and design, carrying out the investigation, presenting the findings, interpreting, and making conclusions. This article reports on the common weaknesses associated with students' performance in science investigations, and suggests how teachers can help students to carry out practical investigations. An instructional model for teaching science investigation is proposed, and the performance indicators corresponding to each stage of the investigation is discussed.

Conducting practical science investigation involves interaction between 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 students 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. These involve the design of the task, measurement, data handling and evaluation of the investigative 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 of patterns and dealing with multivariate data. Finally, concepts relevant to evaluation of the task include the reliability and validity of the ensuing evidence.

Common Weaknesses Associated with Students' Performance in Investigations

When conducting investigations, many students encounter difficulties. Common performance weaknesses related to the various aspects of an investigation are discussed below. These are summarised in Table 1.

Table 1.
Common weaknesses in students' performance on investigations.

Aspect of Investigation	Common Performance Weakness
Activating prior knowledge	• Not identifying knowledge relevant to problem at hand, applying theoretical knowledge from textbook, or invoking practical knowledge from real-life experiences • Having preconceptions and misconceptions that would lead to making wrong predictions and observations, and wrong interpretation of data
Planning and design	• Not identifying, controlling, and manipulating appropriate variables for a fair test • Not planning how to manipulate and measure variables • Inadequate choice of scale, range and interval of values • Not planning how to record and organise data to be collected • Not thinking through the details of the procedure
Carrying out the investigation	• Inappropriate handling of equipment leading to inaccurate measurements, wrong interpretation and conclusions • Not controlling relevant variables • Using a limited range of values • Not taking repeated measurements
Presenting the findings	• Using only text to describe or record information – may be too scanty or too wordy • Not indicating what lists of numerical data represent • Not using a table with labelled organising column headings to present data concisely • Not using charts and graphs to visually present data • Confusion over use of bar charts and line graphs • Omitting units of measurements and labels
Interpreting and making conclusions	• Unable to make sense of recorded data • Making interpretations based on inadequate control of variables • Ignoring the data and adjusting the results to match preconceived notions • Arriving at a conclusion that does not follow from the findings or that does not address the investigative question • Little or no reflection on method, findings and conclusion

Activating Prior Conceptual Knowledge

Students sometimes have difficulty identifying knowledge that is relevant to the problem at hand, and putting the theoretical knowledge they have gained from the textbook to practical use in investigative tasks. For investigations that involve more real-life personal experience than textbook knowledge, students sometimes also do not invoke much of their experiential knowledge. Thus, this knowledge remains inert. Students' preconceptions and misconceptions, if strongly entrenched, may lead them, not only to make wrong predictions, but also to arrive at incorrect results and conclusions, despite experimental findings that show otherwise. For example, several students have the mistaken notion that metal or aluminium foil, being good conductors of heat and being able to get hot fast, would also be suitable materials to be wrapped around a beaker of hot water to keep it hot for a long time (Chin & Kayalvizhi, 2002).

Planning and Design

Students frequently lack problem analysis and planning skills (Hackling & Garnett, 1995). They often work on an activity without purpose and carry out an experiment in a mechanical, unthinking way (Watson, 1994). Sometimes, they do not plan how they would measure variables or record data before data-collection. Some students do not give much thought to details about the investigations and jump right into the physical manipulations without even drawing up a plan. However, after putting their sketchy plans into action, they are confronted by many unforseen problems.

Students often face difficulties with identifying, controlling and manipulating appropriate variables to make an investigation a fair test (e.g. Donnelly, 1987; Duggan, Johnson & Gott, 1996). They also have problems in identifying independent variables as continuous, where appropriate, and when the number of independent variables is more than one, they ignore or overlook relevant control variables. In addition, students also find investigations dealing with multiple and continuous variables more difficult than those involving single, categorical variables (Gott & Duggan, 1995).

Carrying Out the Investigation

Several weaknesses in performance can lead to inaccurate measurements and consequently wrong interpretations and conclusions. These include inappropriate handling of equipment (e.g. lifting a thermometer out of water into the air when reading the temperature), not identifying control variables and keeping them constant, and using an insufficiently large range of values or too short a time interval (e.g. less than 1 min, which is insufficient to detect any significant temperature differences). Few students repeat observations or measurements, or make notes during an investigation other than recording measurements (Harlen, Black & Johnson, 1981). They often take measurements only once instead of two or three times to find an average. Even if they have been taught to take repeated measurements, many students may not internalise this concept nor understand the rationale and significance of doing this. The students are often eager to finish the investigation as quickly as possible and try to take short cuts, 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.

Presenting the Findings

Students can use either text, drawings, tables, charts or graphs to communicate their findings, depending on the nature of their data. One common weakness is to use only text to simply describe or record information, which may be either too scanty or too wordy. Using tables, where appropriate, helps to organise and summarise essential information concisely. Charts and graphs can also be used to visually represent data; this facilitates the detection of patterns and trends. Students sometimes plot line graphs when the use of bar charts would be more appropriate. They also do not indicate the units of measurement correctly or omit them altogether.

Other common problems in students' presentation of results include (a) not indicating what a list of numerical data represent and not using labelled column headings to organise such data; (b) recording the same units of measurement repeatedly throughout the table for every reading instead of only once at the top in the column heading; and (c) using too many unnecessary words or sentences to record numerical data. For the latter problem, a more succinct representation of the data in the form of a table would make it easier to interpret trends and patterns.

Interpreting and Making Conclusions

Sometimes, students do not know how to make use of their data recorded, make interpretations based on inadequate control of variables (Hackling & Garnett, 1995) or arrive at a solution to the problem without even interpreting the results obtained (Watson, 1994). Some students make conclusions which are not based on the results obtained; their conclusions have little or no connection with the question posed in the problem. For example, in an investigation to find out which is the best material to wrap around a beaker of hot water to keep it hot for the longest time, a student is unable to make any sense of the temperatures recorded at different times for various materials, and writes as conclusion: "As we change the temperature of water, the level of the thermometer [mercury thread] increases". In some cases, the interpretations or conclusions made do not follow from the findings, possibly because of the influence of strongly entrenched misconceptions (e.g. aluminium foil is the best material for keeping a beaker of water hot). Students may ignore or even fudge their data and adjust their results to match their preconceived notions (Chin & Kayalvizhi, 2002).

Helping Students carry out Investigations

The following suggestions on how teachers can guide their students to carry out investigations are structured around the main stages involved in investigations, namely (a) pre-investigation, (b) planning and design, (c) carrying out the investigation, (d) analysis, interpretation and presentation of results, and (e) post-investigation. The ideas are encapsulated in the 5PI2R instructional model for facilitating investigations (Fig. 1) which depicts the investigative process as dynamic and iterative with feedback loops. The acronym, 5PI2R, represents the focus of each stage (viz. **P**roblem definition, **P**rior knowledge, **P**rediction, **P**lan, **P**rocedure, **I**nvestigation, **R**esults and **R**eflection) of the investigation.

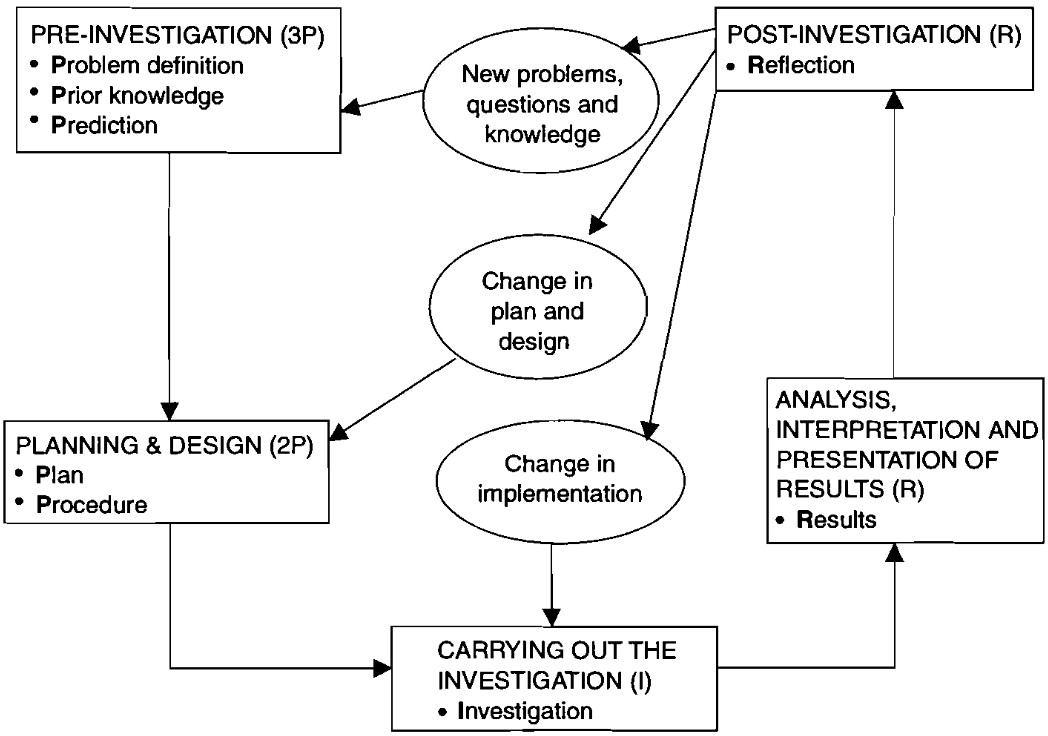

Fig. 1. The 5PI2R instructional model for science investigations.

Pre-Investigation

The focus of this stage is problem definition and the elicitation of students' prior knowledge and predictions. Students' questions and problems are not always expressed in ways which are amenable to practical investigations (e.g. "Why does salt dissolve in water?"). The teacher could help students translate such questions into testable hypotheses or reformulate the problem to an investigable one (e.g. "What factors affect how much salt dissolves in water?"). Also, students are sometimes unable to identify relevant and useful prior knowledge in connection with the problem under investigation. The teacher could elicit students' prior conceptions and predictions related to the topic, and make this explicit to the students. This diagnostic phase would provide valuable feedback to the teacher about students' thinking and misconceptions. It would also make students more aware of their own ideas, hypotheses, and predictions of possible outcomes, and more conscious of what they know and do not know regarding the problem.

Encouraging students to identify relevant prior knowledge and make predictions are important aspects of the pre-investigative phase as these skills have been found to be intimately related to the ability to identify relevant variables and interpret data (McNay & Melville, 1993). Furthermore, as theoretical speculation often precedes experimentation and the search for evidence in the real world of the scientist, it is pedagogically useful to engage learners in theorising in advance (Hodson, 1992a).

Planning and Design

The focus is on the investigational plan and procedures. Teachers need to emphasise the importance of drawing up a detailed plan and anticipating potential problems. For example, students could identify the materials to be used, the type of variables involved (control, independent, dependent), and determine how the variables can be manipulated, controlled and measured. In the case of investigations involving biological variation, students would need to consider appropriate sample size.

Students can present their designs, investigational plans and methodology so that the teacher can provide feedback, vet their plans and advise them against potential pit-falls. They can also anticipate possible problems that they may encounter and plan how they would record and present their data. Instead of having the "results table" pre-drawn for them as found in some activity workbooks, teachers can require students to think about how they could best present their findings. For example, they could use the table as an advance organiser or planner to show the type, number, range and interval of values of their variables, and label their column headings *before* rather than after collecting their data. Selecting an adequate range of values and a suitable number of readings would allow a sufficient spread of reasonably spaced data so that whole patterns can be discerned.

These first two stages (viz. pre-investigation, planning and design), which involve eliciting students' prior ideas and proper planning, are important in providing students with a mental framework and a state of readiness before they proceed to the data-collection phase. Students will then be better prepared to carry out their investigations more thoughtfully and meaningfully.

Carrying Out the Investigation

The students implement their plans and physically manipulate materials. Teachers need to check that students handle apparatus and equipment properly (e.g. light a Bunsen burner with the air hole closed, read meniscus of liquids at eye-level, do not take a thermometer out of a liquid to read the temperature or use it as a stirrer), manipulate and control the appropriate variables, and take repeated measurements. Other behaviour to pay attention to include whether students take measurements accurately and record their data directly onto the appropriate spaces or tables in their worksheet.

Analysis, Interpretation and Presentation of Results

In recording their data and communicating their results, students should be taught how to order their data and present their findings using appropriate displays that convey all essential information as succinctly as possible. This would allow underlying relationships between variables to be detected more clearly, and facilitate comparison and interpretation of data. Diagrams, tables and graphs should be given a title. Diagrams of biological specimens and experimental set-ups should be labelled. Drawings should have a clear outline, with correct proportion, giving details, and magnification, when appropriate. Tables should have descriptive column headings and units indicated, if applicable. Numerical data should be recorded to the same and appropriate number of decimal places, depending on the degree of precision related to the instruments used. Axes of graphs should also be labelled, indicating what they represent and the units involved.

Students can use bar charts to visually represent data that involve a categoric, independent variable (defined descriptively). However, if continuous variables (which are defined numerically) are involved, a line graph would be more appropriate. Students could also be taught how to draw a line of best fit when drawing line graphs. This explicit teaching of the communication of science is necessary and important, given the findings by Campbell *et al.* (2000) that even undergraduates were unable to communicate properly, the conduct and findings of their laboratory investigations. Actual samples of students' work, which depict the various ways in which students present their findings can be shown to the class. Students then critique and discuss the relative merits and weaknesses of each response. They can compare and learn from the exemplars as well as from their own mistakes.

Students should be taught that their conclusion should make a statement that directly answers the question posed in their investigative problem, which is consistent with and follows from their data, and is linked to the purpose and findings. A conclusion should not merely repeat the results obtained, but go beyond this by attempting to identify relationships between variables and generalisation based on patterns in the data. After completing their investigations, the groups could also present their results orally and answer any questions posed to them, with the teacher helping to consolidate their knowledge and summarising the key points. This would help students to think critically about the reliability and validity of their evidence.

Post-Investigation

A post-investigation phase, which is often overlooked, is also important where students engage in critical reflection and self-evaluation, and take stock of what they have done and how they have done it. Students think about any anomalous data, possible sources of error when making measurements, any changes they would make if they were to repeat the investigation, how they would improve on the design or the methods used, the implications or significance of their findings,

Table 2.
5PI2R performance indicators for investigative tasks.

Pre-investigation (3P: Problem definition, Prior knowledge, Predictions)	
• Problem is clearly defined, question is testable and investigable	✓
• Hypothesis is postulated (if applicable)	✓
• Prediction is made	✓
Planning and Design (2P: Plan, Procedure)	
• Correctly identified key variables as independent and dependent	✓
• Identified variables appropriately as categoric or continuous	✓
• Identified appropriate control variables for fair test	✓
• Planned how to manipulate and measure independent variable	✓
• Planned how to measure dependent variable	✓
• Identified suitable materials and equipment to be used	✓
• Planned how to record and organise data to be collected (e.g. table)	✓
• Scale, range, interval, number of values chosen are adequate and reasonable	✓
• Appropriate sample size (if relevant)	✓
• Method chosen is suitable (e.g. fair test, survey, etc.)	✓
Carrying out the investigation (I: Investigation)	
• Handled instruments and equipment appropriately to give suitable accuracy	✓
• Repeated measurements (if necessary)	✓
• Kept control variables constant	✓
• Manipulated independent variables appropriately	✓
Analysis, interpretation and presentation of results (R: Results)	
• Described method in sufficient detail	✓
• Diagram/table/graph given sufficiently descriptive titles	✓
• Diagrams are labelled and drawn to correct proportions (if applicable)	✓
• Used table to organise data, with descriptive column headings and units indicated	✓
• Recorded numerical data to appropriate number of decimal places	✓
• Determined average of repeated measurements (if applicable)	✓
• Graph drawn (or omitted), as appropriate	✓
• Axes of graph labelled, with units indicated, and scale suitably chosen	✓
• Line of best fit drawn appropriately (if applicable)	✓
• Patterns and underlying relationships in data interpreted correctly	✓
• Conclusion made is clear and succinct, consistent with data, relates to the aim and directly answers the investigative question posed	✓
Post-investigation (R: Reflection)	
• Identified possible sources of error in measurements	✓
• Identified anomalous data, if any	✓
• Suggested changes for improvement in design or methods	✓
• Asked thoughtful questions regarding the design, implications or significance of findings	✓

Note: Indicators to be used, as appropriate, depending on the nature of the investigation.

and any further questions that they have. As many students do not seem to think about these things spontaneously, the teacher can explicitly require them to do so. Over time and with regular practice, these cognitive behaviours may become habits. Students' questions can also provide valuable information for the teacher about what is puzzling the students and what they want to know.

Table 2 shows the investigative stages of this model and the associated performance indicators. These indicators purposefully address each of the common performance weaknesses displayed by students. They may be used in a checklist, where appropriate and applicable, to help teachers monitor and assess their students' performance in scientific investigations. In this way, a profile of each student's performance strengths and weaknesses may be constructed.

Teaching About Investigations

To guide students in carrying out an investigation, teachers could provide scaffolding questions on a planning or prompt sheet (Hackling & Fairbrother, 1996; Watson & Fairbrother, 1993) to help students focus on various aspects of the investigation such as identifying the purpose, linking to prior knowledge, predicting, explaining and consolidating their knowledge. These questions might include "What is the problem that you are investigating?", "What do you think will happen?", and "What have you found out that you did not know before?". Alternatively, statement stems such as "What I am going to find out is . . .", "What I already know about this. . . .", "I think this will happen because . . ." could be provided.

Different from conventional worksheets, they help students to actively think about what they are doing, both in drawing upon their knowledge and understanding, and in their investigative strategies. This helps them to focus on the task at hand, encouraging them to think through concepts and procedures required for the actual conduct of the investigations. The worksheet would also give teachers insight into: (a) how the students have interpreted the problem, (b) the ideas the students are bringing to the investigation and what they expect to happen, and (c) students' reflections on the process of investigating and their learning outcomes.

Students need to be familiar with the concepts and language associated with investigations (e.g. independent, dependent, and control variables; hypothesis; fair test; range and interval) so that they can use the appropriate language to articulate their ideas. The teacher also needs to emphasise to the students, the reasons and rationale underlying each of the procedural steps taken. That is, the students should know why they are doing what they are doing. For example, students should understand why they have to take repeated measurements instead of merely carrying out this step ritualistically as part of a prescribed algorithm. In this way, they are more likely to view the various tasks associated with an investigation as meaningful components of a coherent whole that would contribute to the reliability and validity of their findings.

Conclusion

As skills and processes cannot be divorced from the knowledge and theories to which they are inextricably bound, transfer is most likely to occur when the domains in which they are acquired are related, and when transfer is explicitly taught (Wellington, 1989). There is an interaction between process skills and contexts (Song & Black, 1991). Some skills (e.g. planning) are generalisable but others (e.g. observation) are context-dependent (Lock, 1990; Toh & Woolnough, 1994). Also, skills such as planning and interpretation are strongly related to one another, whereas performance on observation and reporting are relatively distinct (Lock, 1989).

As the performance of individuals on investigations is not independent of content, context, and theory-independent processes, teachers should be mindful not to organise their instruction around activities that focus on the process skills as independent entities (Hodson, 1992b; Millar, 1989; Millar & Driver, 1987) and assume that these skills are transferable to contexts which differ from that for which they were originally acquired. Such a practice may unwittingly lead students to "concentrate on a large number of discrete, decontextualised practical skills" (Woolnough & Allsop, 1985). The pre- and post-investigative phases, which aim to help students integrate their process skills and conceptual knowledge into a more coherent whole, would take into account the dynamic, iterative and reflective nature of real scientific inquiry. Students also need practice in applying these skills and concepts over several investigations and across a variety of contexts.

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References

Campbell, B., Kaunda, L., Allie, S., Buffler, A. & Lubben, F. (2000). The communication of laboratory investigations by university entrants. *Journal of Research in Science Teaching*, **37**(8), 839–853.

Chin, C. & Kayalvizhi, G. (2002). Open-ended investigations in science: A case study of primary 6 pupils. *Journal of Science and Mathematics Education in Southeast Asia*, **25**(1), 70–94.

Donnelly, J. F. (1987). Fifteen-year-old students' variable handling performance in the context of scientific investigations. *Research in Science and Technological Education*, **5**(2), 135–147.

Duggan, S. & Gott, R. (1995). The place of investigations in practical work in the UK National Curriculum for Science. *International Journal of Science Education*, **17**(2), 137–147.

Duggan, S., Johnson, P. & Gott, R. (1996). A critical point in investigative work: Defining variables. *Journal of Research in Science Teaching*, **33**(5), 461–474.

Gott, R. & Duggan, S. (1995). *Investigative Work in the Science Curriculum*. Buckingham: Open University Press.

Hackling, M. W. & Fairbrother, R. W. (1996). Helping students to do open investigations in science. *Australian Science Teachers' Journal*, **42**(4), 26–33.

Hackling, M. W. & Garnett, P. J. (1995). The development of expertise in science investigation skills. *Australian Science Teachers Journal*, **41**(4), 80–86.

Harlen, W., Black, P. & Johnson, S. (1981). *Science in Schools: Age 11: Report No.1*. London: DES.

Hodson, D. (1992a). Redefining and reorienting practical work in school science. *School Science Review*, **73**(264), 65–77.

Hodson, D. (1992b). Assessment of practical work: Some considerations in philosophy of science. *Science & Education*, **1**, 115–144.

Lock, R. (1989). Assessment of practical skills. Part 1: The relationships between component skills. *Research in Science and Technological Education*, **7**(2), 221–233.

Lock, R. (1990). Assessment of practical skills. Part 2: Context dependency and construct validity. *Research in Science and Technological Education*, **8**(1), 35–52.

McNay, M. & Melville, K. W. (1993). Children's skill in making predictions and their understanding of what predicting means: A developmental study. *Journal of Research in Science Teaching*, **30**(6), 561–577.

Millar, R. (1989). What is 'scientific method' and can it be taught? In J. Wellington (Ed.), *Skills and Processes in Science Education* (pp. 47–62). London: Routledge.

Millar, R. & Driver, R. (1987). Beyond processes. *Studies in Science Education*, **14**, 33–62.

Song, J. & Black, P. J. (1991). The effects of task contexts of students' performance in science process skills. *International Journal of Science Education*, **13**(1), 49–58.

Toh, K. A. & Woolnough, B. E. (1994). Science process skills: Are they generalisable? *Research in Science and Technological Education*, **12**(1), 31–42.

Watson, J. R. (1994). Students' engagement in practical problem solving: a case study. *International Journal of Science Education*, **16**(1), 27–43.

Watson, R. & Fairbrother, B. (1993). Open-ended work in science (OPENS) project: managing investigations in the laboratory. *School Science Review*, **75**(271), 31–38.

Wellington, J. (1989). Skills and processes in science education: An introduction. In J. Wellington (Ed.), *Skills and Processes in Science Education* (pp. 5–20). London: Routledge.

Woolnough, B. & Allsop, T. (1985). *Practical Work in Science*. Cambridge: Cambridge University Press.