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PRIMARY AND SECONDARY SCHOOL STUDENTS' ATTAINMENT OF SCIENCE INVESTIGATION SKILLS

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ABSTRACT

A practical test instrument was developed to assess students' attainment of skills associated with problem analysis and planning experiments, collecting information, organising and interpreting information, and concluding. Students verbalised their thoughts as they worked on the task and their performance was videotaped for analysis. Data collected from Year 7, 10 and 12 science students illustrate the development of investigation skills and reveal important areas of student weakness.

INTRODUCTION

Woolnough and Allsop (1985) have identified three aims that can validly be achieved through laboratory work: the development of process skills and laboratory techniques; getting a feel for phenomena; and being a problem-solving scientist. Several authors have argued that scientific problem-solving skills can be developed through inquiry oriented or investigation style laboratory work that gives students opportunities to practise the skills of problem analysis and planning experiments, collecting data, and organising and interpreting data (Tamir & Lunetta, 1981; Woolnough & Allsop, 1985; Tamir 1989). Johnstone and Wham (1982) have cautioned that inquiry oriented, investigation style laboratory work is cognitively demanding and that informational inputs may overload working memory capacity. Experts cope more easily in these high information situations as they have developed automated, proceduralized routines for common processing tasks thus freeing-up working memory capacity for dealing with novel aspects of the problem, planning, monitoring and control of processing (McGaw & Lawrence, 1984; Anderson, 1985).

Experts bring extensive domain specific schema knowledge to problem-solving tasks which enables them to generate high quality problem representations which guide the selection of efficient solution processes (Chi, Feltovich & Glaser, 1981). Experts spend more time on problem analysis (Larkin, 1979), do more high level metaplanning (Hayes-Roth & Hayes-Roth, 1979), and demonstrate greater metacognitive control over processing than novices (Schoenfeld, 1986). This paper reports on a study which examines the development of science investigation skills through primary, junior high and senior high school science education.

PURPOSE AND RESEARCH QUESTIONS

The purpose of this study was to examine the problem-solving processes used by Year 7, Year 10 and Year 12 science students when conducting a laboratory-based science investigation. More specifically, the study addressed two research questions:

1. Which process skills are Year 7, Year 10 and Year 12 science students able to apply in the problem analysis and planning, data collection, data interpretation and concluding phases of a laboratory investigation?

2. What factors appear to limit students' success on practical problem-solving tasks?

METHOD

Subjects

In Western Australia Year 7 is the last year of primary school, Year 10 is the last year of junior high school, and Year 12 is the last year of senior high school. A modified random stratified sampling technique was used to select a total of 10 students from each of Years 7, 10 and 12. All students were from the top half of the population in terms of science achievement. Each sample comprised two students from each of five different schools, four students from church schools and six students from state schools, and equal numbers of males and females. The Year 12 sample comprised equal numbers of students studying either biological or physical sciences.

Procedure

The open-ended, problem-solving task was administered to subjects individually. No time limit was imposed on the students' work. Students worked on the task with concurrent verbalisation (Ericsson & Simon, 1980; Larkin & Rainard, 1984). There was minimal interruption from the experimenter except for encouragement to verbalise and for the debriefing session at the end of the task. Subjects' verbalisations and apparatus manipulations were recorded on videotape. A coding manual guided the dual and independent coding of the videotapes by two trained coders. Coding discrepancies were resolved at meetings between the coders and the investigator.

Instrument Context. The task was set in the context of engineers who design and build bridges and need to understand the factors that influence the bending of beams under load. Subjects were shown a picture of a truck passing over a bridge.

The Task. Think-aloud procedures were modelled for the subject by the investigator, and subjects practised verbalising on two arithmetic problems. The task was explained to the subject and then the subject commenced work by reading aloud the task statement presented in Figure 1.

THE TASK
Find out what factors influence the bending of beams under load

REMEMBER
I would like you to
plan and carry-out experiments,
record and interpret your results,
and state your conclusions

Fig. 1. The Task Statement

Apparatus. Figure 2 illustrates the apparatus provided for the subject at the start of the session. A wooden beam was supported by two retort stands and a load of slotted masses was suspended from the centre of the beam. A 1 m rule and a 50 cm rule lay on the bench, and a 30 cm plastic rule held vertical by a retort stand was placed next to the beam. Additional slotted masses were available on the bench. A pencil, ruler, pad and graph paper were placed to the side of the beam. The subject was shown a large opaque plastic tube which contained a range of other beams of different diameters, cross-sectional shapes and materials that the investigator would supply to the subject on request. Subjects were not permitted to examine the types of beams in the tube so they had to generate beam variables themselves rather than just cue-in to variables displayed by the selection of beams.

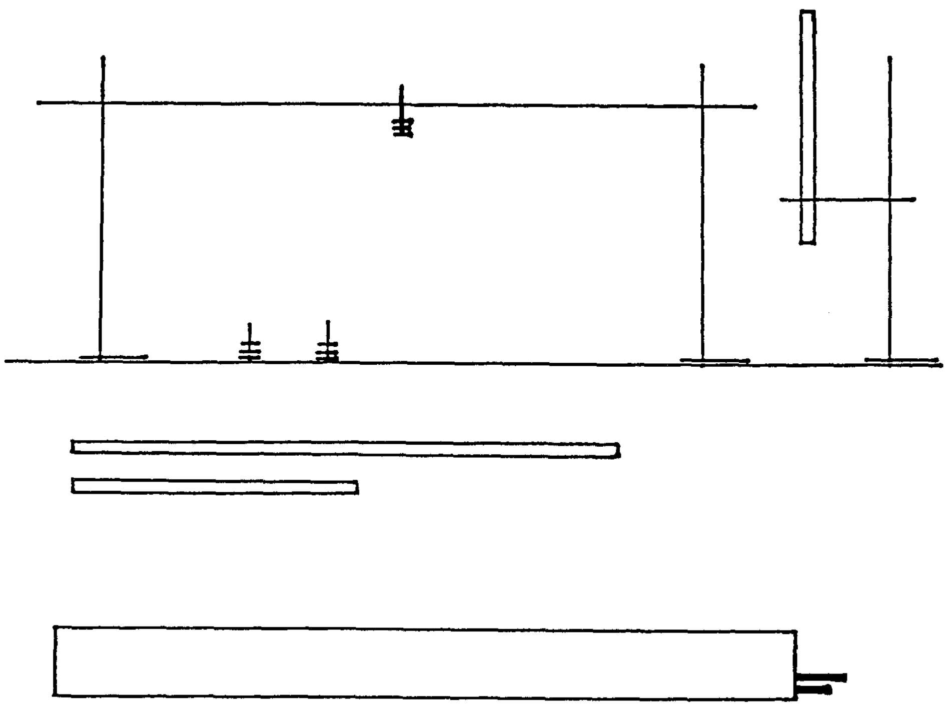

Fig. 2. Apparatus Provided for the Investigation

RESULTS

Results are presented in terms of the process skills displayed by subjects during the four phases of the investigation: (1) analysis of the problem and planning, (2) collecting information, (3) organising and interpreting information, and (4) concluding.

(1) Analysis of the Problem and Planning

One of the most distinct features of the students' problem solving was the limited amount of problem analysis and planning done before manipulating the equipment and collecting data. This is illustrated by the data presented in Table 1.

TABLE 1
STUDENT BEHAVIOURS ASSOCIATED WITH
ANALYSIS OF THE PROBLEM AND PLANNING

Behaviours	Student year group		
	Year 7 (n = 10)	Year 10 (n = 10)	Year 12 (n = 10)
Number who commenced by identifying potential independent variables	3	5	7
Stated an aim or purpose for an experiment	1	3	4
Planned how a variable would be applied or measured in an experiment	0	0	6
Verbalised an intention to control variables	0	0	0
Planned data recording	0	0	2
Planned an overall approach to the investigation (metaplanning)	0	0	0

Many students commenced by identifying potential independent variables, although most independent variables (81 of 128) were identified while students were involved with experimenting. Only a small number of subjects (8 of 30) stated an aim or purpose for their experiments. Only six students, all in Year 12, planned how they would apply or measure variables in their experiments. None of the students verbalised an intention to control variables. Only two subjects planned their data recording before commencing data collection. None of the students planned an overall approach to their investigation. Inspection of Table 1 reveals a trend towards greater problem analysis and planning from Year 7 to Year 12.

(2) Collecting Information

On average the students each conducted 3.1 experiments. The number of experiments ranged from a minimum of none to a maximum of seven experiments per student. An experiment consisted of tests of a particular independent variable. There were six main independent variables that could be tested: beam length, thickness, cross-sectional shape and material; load size, and location of the load along the beam. Data regarding students' experimenting are presented in Table 2.

TABLE 2
STUDENT BEHAVIOURS ASSOCIATED WITH COLLECTING INFORMATION

Behaviours	Student year group		
	Year 7 (n = 10)	Year 10 (n = 10)	Year 12 (n = 10)
Mean number of			
Experiments performed	2.1	3.9	3.3
Measured changes in the dependent variable	4	5	6
Measured zero values for dependent variable	1/4[a]	3/5	6/6
Avoided parallax errors with measurements	1/4	4/5	6/6
Measurements made at point of maximum deflection of the beam	0/4	4/5	5/6
Controlled variables by standardising measurement procedures	0/4	4/5	6/6
Controlled variables when changing beams	1	2	5

Note. [a] One of the four students who made measurements, measured zero values.

Half of the students made no measurements of the dependent variable, they relied on qualitative comparisons of the amount of bending of different beams. Of the six Year 12 students who measured the dependent variable all measured zero values and took care to avoid parallax error. Five of the six subjects also measured beam bending at the point of maximum deflection. Most subjects collected data over a rather small range of values for the independent variables.

Control of variables could be demonstrated in three ways in this investigation. First, students could standardise their measurement procedures, for example, measuring bending in the centre of the beam, using standard loads and beam lengths when comparing different beams. All Year 12 students who measured bending standardised their measurement procedures in this way, four of the five Year 10 students who made measurements also standardised their procedures, however none of the four Year 7 students who made measurements demonstrated any awareness of the need to standardise measurement procedures. Second, subjects could demonstrate control of variables when they changed beams. For example when testing the independent variable of beam thickness, subjects could request a thicker beam of the same material and cross-sectional shape. Only eight of the 30 students demonstrated control of variables when changing beams, and as expected most of these were from Year 12. Third, students could also demonstrate control of variables when comparing the bending observed in different experiments. These data are reported in the next section.

(3) Organising and Interpreting Information
Data regarding students' organisation and interpretation of results are presented in Table 3.

TABLE 3
STUDENT BEHAVIOURS ASSOCIATED WITH
ORGANISING AND INTERPRETING INFORMATION

Behaviours		Student year group	
	Year 7 (n = 10)	Year 10 (n = 10)	Year 12 (n = 10)
Number of students who recorded data	3	5	8
in tabular form	0/3[a]	1/5	6/8
with units	0/3	3/5	6/8
with column headings	0/3	0/5	5/8
Number of students who transformed data into a			
restructured table	0	0	2
graph	0	1	1
Number of students who made uncontrolled data interpretations	4	2	5

Note. [a] None of the three students who recorded data did so in a tabular form.

Only 16 of the 30 students recorded data; of these 16, seven recorded their data in ruled-up tables, nine included units, and five used column headings in their tables. Four students transformed their data into a form that would help them identify patterns in the data; two students collated their data into restructured tables, and two students constructed a graph to help determine the relationship between the independent and dependent variables.

All subjects made some attempt to interpret their experimental findings in terms of variables that influenced beam bending under load. Eleven students made uncontrolled data interpretations, that is, when comparing the bending observed in different trials these students failed to restrict such comparisons to trials that differed in terms of one variable. Only one subject was aware that a comparison of beams of different cross-sectional shape had to be performed using beams of the same cross-sectional area.

(4) Concluding
Once experimental work was completed students summarised their findings. Data regarding students' conclusions are presented in Table 4.

TABLE 4
STUDENT BEHAVIOURS ASSOCIATED WITH CONCLUDING

Behaviours	Student year group		
	Year 7 (n = 10)	Year 10 (n = 10)	Year 12 (n = 10)
Mean number of valid factors identified [a]	1.1	1.8	2.5
Number of students who went beyond their data in drawing conclusions	5	5	1
Number who recognised methodological limitations of their investigation	0	2	5

Note.[a] These are the factors influencing beam bending that were identified and experimentally validated by the students.

Year 12 students, on average, identified and gathered experimental data to support 2.5 factors that influence the bending of beams under load. Year 10 students (1.8) and Year 7 students (1.1) were less successful in the identification and validation of factors influencing beam bending.

When prompted in the debriefing, all subjects attempted to apply their experimental findings to the problem of designing a bridge that would withstand heavy loads. Most subjects identified the need for thick beams and supporting columns placed close together. Half of the Year 7 and Year 10 students went beyond their data when recommending features for the design of the bridge whereas only one of the Year 12 students made this type of error.

In the debriefing, students were also asked how they would improve their approach to the investigation if given another opportunity to work on the problem. All students demonstrated little awareness of the methodological limitations of their investigations. Four subjects said they would take more care with measurements, one subject said he would do more written planning, another said she would test one variable at a time, and another said he would test more beams.

DISCUSSION

The subjects were confronted with a novel problem-solving task set in a real-world context. Expert problem solvers analyse problems and identify cues that activate relevant knowledge schemas to create a mental representation of the task that can facilitate the planning of appropriate solution processes (Chi et al., 1981). Several Year 7 students failed to represent the problem as a task requiring experimental testing of variables. Two Year 7 students performed no tests using the apparatus, only four made any measurements of bending, and only three students recorded any data. It seems that the Year 7 students lacked experience of systematic testing and measurement of experimental variables.

Previous studies of problem solving in science and social science indicate that extended periods of problem analysis and solution planning ultimately lead to efficient problem solutions (Larkin, 1979; Voss, Tyler & Yengo, 1983). The most notable feature of the students' work was their lack of problem analysis and planning before commencing on data collection procedures. Fifteen of the 30 students commenced work by identifying two or three potential independent variables and then almost immediately started manipulating the apparatus to test one of the variables they had identified. Very few students planned how they would apply or measure variables or record data before they commenced data collection procedures. There was no high level up-front metaplanning (Hayes-Roth & Hayes-Roth, 1979) of an overall approach to the problem. In fact most planning was low level, task specific planning in response to circumstances that arose during experimental work, typical of that revealed by previous research into adolescents' planning (Lawrence, Dodds & Volet, 1983). Many students demonstrated a lack of metacognitive control over processing (Schoenfeld, 1986). One Year 12 student performed the same repetitive measurement routine for 25 minutes without any overt monitoring or reflection on the usefulness of the process he was performing.

The students appeared to lack a well-developed schema for the structure of a controlled experiment. Only four students used the term hypothesis and no student used any of the terms variable, independent variable, dependent variable, control of variables, repeated trials or sample size while working on the problem. None of the students verbalised an intention to control variables. Miller and Driver (1987), and Rowell and Dawson (1989) would argue that reasoning skills such as control of variables are developed in particular contexts and are difficult to abstract and generalise to the level where they can be applied easily to novel tasks in unfamiliar domains. Many Year 12 students did however control variables at the level of being systematic in measurement procedures of which they would have had extensive experience.

The Year 12 students used effective measurement procedures taking care with zero values and parallax error. The high school students' relative success on the data collection phase of the investigation versus the planning and analysis phase is likely to be a reflection of the style of laboratory work to which students have been exposed. Analyses of the implemented curriculum in the USA (Tamir & Lunetta, 1981), Israel (Friedler & Tamir, 1984) and Australia (Tobin, 1986) indicate that most high school practical work involves recipe style exercises that are at the lowest level of openness to student planning (Tamir, 1989). Such exercises give students much practice in data collection procedures but no opportunity to practise problem analysis and planning.

The concluding phase of the investigation revealed two further limitations of the students' understanding of experimentation. First, half of the Year 7 and Year 10 students went beyond their data in drawing conclusions or applying their findings to the design of a bridge. Most of the Year 12 students were however more restrained in only drawing conclusions for which they had gathered supporting evidence. Second, even when prompted, very few students could identify limitations in their experimental procedures which suggests that they were unaware of the numerous interfering variables that influenced their experimental findings. It is likely that these students would place unwarranted confidence in their conclusions.

CONCLUSIONS

Results from this study indicate that students at all levels had poorly developed skills of problem analysis, planning and carrying out controlled experiments, basing conclusions only on obtained data, and recognising limitations in the methodology of their investigations.

Many of the Year 7 students failed to represent the task as one requiring experimental testing of variables, in fact most of these students did not make any measurements or record any data. Despite curriculum developments over the last twenty years there appears to be a continuing need to emphasise in the science curriculum of primary schools those activities where students are required to identify and manipulate variables, make measurements and record data.

The high school students showed gradual improvement in their abilities to successfully apply the process skills associated with measurement, data recording and some aspects of data interpretation. Their success on the problem-solving task was limited by ineffective problem analysis, planning, and control of variables.

If high school students are to develop a comprehensive repertoire of science investigation skills there is a need to modify the implemented curriculum to include more investigation style laboratory activities through which students can have the opportunity to practise the skills of problem analysis and planning controlled experiments. There is also a need to explicitly teach the conceptual knowledge regarding the structure of controlled experiments, particularly the concepts of hypothesis, independent, dependent and controlled variables.

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