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ABSTRACT

In investigative work, pupils encounter relatively open-ended tasks for which they have to devise their own solutions. Historically, the development of investigative work in the United Kingdom has come to the point where many schools are adopting it with some enthusiasm and with a degree of success. Progression has been largely defined by the complexity of the tasks as described by the number and type of variables. This paper considers progression in procedural understanding in the context of investigative work in science. The paper looks at the rationale for the inclusion of procedural understanding as a substantive element of a curriculum and details its possible content. An example drawn from an extensive research base is used to illustrate the problems pupils, ages 9-14, have with one element of procedural understanding. It is concluded that the search for progression has some of its elements in place but until teachers are operating a scheme of work which incorporates procedural understanding and its associated content explicitly, the search for progression can only be tentative and provisional. (Author/JRH)

Innovation and Change in Education

PROGRESSION IN INVESTIGATIVE WORK IN SCIENCE

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PROCEDURAL AND CONCEPTUAL KNOWLEDGE IN SCIENCE PROJECT (the PACKS Project)

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PROGRESSION IN INVESTIGATIVE WORK IN SCIENCE

Abstract

This paper considers progression in procedural understanding in the context of investigative work in science. It looks at the rationale for the inclusion of procedural understanding as a substantive element of a curriculum and details its possible 'content'. An example drawn from an extensive research base is used to illustrate the problems pupils have with one element of procedural understanding and suggests that the search for progression in the science curriculum has some way to go.

1. Introduction

Historically, the development of investigative work in science in the UK has come to the point where many schools are adopting it with some enthusiasm and, reports from the Inspectorate suggest, with a degree of success (Office for Standards in Education, 1993). Investigative work in this context is to do with practical work in which pupils encounter relatively open ended tasks for which they have to devise their own solutions. Investigations are, of course, a statutory commitment within the UK National Curriculum, but it is one thing to prescribe an innovation and quite another to effect a real change. Fullan (1991), in discussing educational change, points to the loose relationship between *initiation* and *implementation*. In investigative work, what is still missing, is a coherent rationale both for the place of investigations within the curriculum, and for progression within them.

Progression in a curriculum relies on there being a number of factors in place:

- there must be an agreed set of endpoints,
- there must be an agreed content, described in sufficient detail for it to be usable by teachers, and
- the sequencing of the material must be identified against an appropriate level of detail.

In the UK National Curriculum, none of these conditions are met. The same is true of the Australian system which has recently introduced a strand in the science curriculum, 'Working Scientifically', which mirrors to a great extent its counterpart in the UK. It is important, then, that we tackle the problem of progression in investigative work from its root: we need a more complete justification and thereby an agreed endpoint. and content. We will sketch out such a justification here. We will then suggest a possible 'content', defined as a set of skills and understandings, and illustrate one possible element of progression within that content from the research evidence of the project.

2. Science and society

Science education must accomplish two major aims in the context of its role in the wider society:

- it must so educate the populace in general that it can contribute to the democratic process with a degree of confidence and
- it must give pupils the necessary knowledge and skills to enter the workforce.

What does an informed public need to know about science to become involved in decision making at all levels of society? It may be best to illustrate this with a simple example, one that has been the focus of attention for a number of years. The Sellafield complex in Cumbria, which is intended to reprocess radioactive waste, has been the cause of much concern amongst residents in the area as to whether or not it is the cause of clusters of leukaemia. The informed citizen may well have some idea of what radiation is but to many, it is an undifferentiated term somehow connected with atomic bombs and reactors. The notion that the radiation comes from material which is itself deposited through rainfall is one which is not generally understood. There is also the point that radioactive materials such as plutonium are of themselves chemically toxic. But having said all that, the public is well aware that radioactivity is dangerous even if they are not certain as to its precise origins. The work in the UK on the public understanding of science has tended to concentrate on providing causal and conceptual explanations of phenomena of this type (see, for example, Layton *et al.*, 1993)

But there is another side to the argument concerned with the evidence which is used by various pressure groups both for and against the contention that radiation from Sellafield is causing the clusters of leukaemia.. We would argue that an informed public needs to be able to look critically at that evidence. There is a need to be aware that the data is capable of different interpretations and to understand that the proponents of the various positions must be able to demonstrate that their evidence is valid and reliable. These are key issues which school science should endeavour to teach. The Royal Society (1985), in discussing the public understanding of science, wrote:

> *.... the individual needs to know some of the factual background and to be able* to assess the quality of the evidence *being presented. Greater familiarity with the nature and the findings of science will also help the individual to resists pseudo-scientific information. An enhanced ability to sift the plausible from the implausible should be one of the benefits from better public understanding of science. (authors' emphases)*

At present, professional scientists are seen by the public as the only arbiters of what is 'truth' in the matter. That need not be the case, and indeed should not be. There are many cases of scientists making bad judgements which indicate that science should not be left to scientists alone. An informed public needs to be able to enter the debate and evaluate evidence, particularly when judgements are made in matters affecting their lives. We would argue that, to date, science education has failed to make pupils aware of and familiar with the ideas surrounding the collection, validation and interpretation of 'objective' evidence.

3. Science and employment

Turning now to the requirements of the workforce in science-related employment. In a liberal education, these requirements cannot be seen to dominate the curriculum, but they are an important factor which must be taken into account, for self-evident reasons. Industry cites the need for 'transferable skills'. But what are they? A recent report from a task group set up by industry and the department of employment (the Council of Science and Technology Institutes, 1993) in the UK gives a picture which can help to define these skills.

The authors of the report developed a framework to describe what scientists, technologists and mathematicians do. They defined the key purpose as being:

To explore, establish, apply, manage and administer safe and ethical practices and procedures of science, technology and mathematics to generate new knowledge, and to exploit this knowledge to serve the economy, the environment and society

To achieve this purpose three 'skills' or abilities were identified:

i A central core of skills concerned with the doing of science

ii Communication skills

iii Management skills

The first of these, the central core of skills or 'transferable skills', are common to a wide range of occupations where science is used. These transferable skills (perhaps better defined as 'common skills' since the evidence of their transferability is not clear) are defined by the authors of the report in more detail as the ability to:

- Generate own ideas, hypotheses and theoretical models and / or utilise those postulated by others
- Design investigations, experiments, trials, texts, simulations and operations
- Conduct investigations, experiments, trials, tests and operations
- Evaluate data and results from the processes and outcomes of investigations, experiments, trials, tests and operations

This is not to argue, of course, that occupations do not require conceptual understanding in the appropriate discipline(s). But what the above does point to is that notions surrounding evidence such as the testing of ideas and the evaluation of data are thought to be important both for the public understanding of science and for the requirements of employment in occupations where science (as well as maths and technology) are a significant part of the job. These headings will not be unfamiliar to those who recall the work in the mid-1960s of the American Association for the Advancement of Science (1989) where similar statements were arrived at which led to the introduction of so-called 'process science'.

However, the process science movement of the 60's and 70's failed to make a significant impact. We wish to argue here that this was largely because the aims, laudable though they were, were prescribed in insufficient detail to be incorporated unambiguously into a curriculum. Neither was there any agreement that the 'processes' might be anything other than a means to the traditional conceptual end; a teaching approach rather than a putative content. It is this failure of recognition of the content of investigative work in its own right that has plagued its development in the UK science curriculum, since without it there are no agreed endpoints, (or content) and therefore no agreed and logical progression.

4. A content description of the science curriculum

A simple model to locate the content of the science curriculum will help in the search both for a justification and an associated content description (fig. 1).

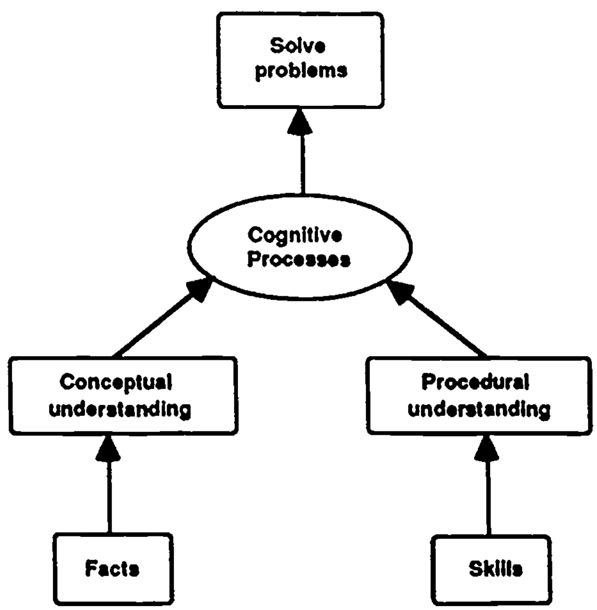

Fig. 1: A model for science (Gott and Duggan, 1994)

Conceptual understanding refers to the understanding of the ideas in science which are based on facts and which are sometimes referred to as 'substantive' or 'declarative' concepts. Examples are energy, the laws of motion, heredity, solubility, photosynthesis and so on. Procedural understanding is the understanding of a set of ideas which is complementary to conceptual understanding but related to the 'knowing how' of science. It is concerned with the understanding needed to put science into practice and can be regarded as *the thinking behind the doing*. Procedural understanding requires the use of 'skills' which here refer to activities such as the use of measuring instruments and the construction of tables and graphs, which are necessary but not sufficient in themselves to the carrying out of most practical work. For example, in measurement in a plant growth study, procedural understanding does not refer to the measuring itself, but to the decisions that have to be made about what to measure, how often and over what time period. It also includes the understanding of the notion of the fair test as well as the nature of a line graph, how it differs from a bar chart or how it illustrates patterns between variables.

An analogy may be useful here. The facts, skills and understandings can be envisaged as information or patterns in the brain's memory bank. When faced with a problem of any sort, but in the sense of some new experience which requires resolution, the brain can be imagined to scan its data banks for facts or previous experiences that may help with the new problem. In the above example, those 'hard disk stores' will contain ideas about speed, measurement of distance and time, skill routines about using instruments, notions of a fair test and how it relates to the validity of any resulting data and so on. The central processing unit will then examine the problem and look on the hard disc for help; this may be in the form of particular ideas, or past experiences in similar circumstances. These will be pulled into the working memory. Then they must be 'processed', via a series of thought patterns that we label hypothesising, or predicting or whatever, into a solution consonant with, and evaluated against, the demands of the original problem.

The elements of science we identified in the introduction, the understandings that underpin both the requirements for democratic decision making and the 'common skills' sought by industry, can be seen to lie in the procedural understanding area of the model. The question now is to produce an (embryonic) content description. Some of the elements are in place in curricula, notably the skills of scientific working and the notion of a 'fair test'. But there are considerable gaps. We have suggested elsewhere that this gap should be occupied by 'concepts of evidence', a term chosen in order to distinguish these understandings from the manipulative connotations of scientific skills. They are outlined in table 1.

Concepts of evidence			Definition
RELIABILITY AND VALIDITY	Associated with design	VARIABLE IDENTIFICATION	Understanding the idea of a variable and identifying the relevant variable to change (the independent variable) and to measure or assess if qualitative (the dependent variable).
		FAIR TEST	Understanding the structure of the fair test in terms of controlling the necessary variables and the importance that the control of variables has in relation to the validity of any resulting evidence.
		SAMPLE SIZE	Understanding the significance of an appropriate sample size to allow, for instance, for biological variation.
		VARIABLE TYPES	Understanding the distinction between categoric, discrete, continuous and derived variables and how they link to different graph types. For example, a categoric independent variable such as type of surface, cannot be displayed sensibly in a line graph. The behaviour of a continuous variable on the other hand is best shown in a line graph.
	Associated with measurement	RELATIVE SCALE	Understanding the need to choose sensible values for quantities so that resulting measurements of the dependent variable will be meaningful. For instance, a large quantity of chemical in a small quantity water causing saturation, will lead to difficulty in differentiating the dissolving times of different chemicals.
		RANGE AND INTERVAL	Understanding the need to select a sensible range of values of the variables within the task so that the resulting line graph consists of values which are spread sufficiently widely and reasonably spaced out so that the 'whole' pattern can be seen. A suitable number of readings is therefore also subsumed in this concept.
		CHOICE OF INSTRUMENT	Understanding the relationship between the choice of instrument and the required range, interval and accuracy.
		REPEATABILITY	Understanding that the inherent variability in any physical measurement requires a consideration of the need for repeats, if necessary, to give reliable data.
		ACCURACY	Understanding the appropriate degree of accuracy that is required to provide reliable data which will allow a meaningful interpretation.
	Associated with data handing	TABLES	Understanding that tables are more than ways of presenting data after it has been collected. They can be used as ways of organising the design and subsequent data collection and analysis in advance of the whole experiment.
		GRAPH TYPES	Understanding that there is a close link between graphical representations and the type of variable they are to represent.
		PATTERNS	Understanding that patterns represent the behaviour of variables which can be uncovered from the patterns in tables and graphs.
		MULTIVARIATE DATA	Understanding the nature of multivariate data and how particular variables within those data can be held constant to discover the effect of one variable on another.

Table 1: Concepts of evidence (Duggan *et al.*, 1994)

The overarching notions of validity and reliability address the question: is the evidence *'believable'* and does it reflect the problem that is to be solved? Only when this has been established can we go on to draw valid conclusions or offer alternative interpretations. This we can represent in the model in fig. 2, in which concepts of evidence and skills are brought to bear on the problem in an iterative way, but one in which the iterations are guided by notions concerning validity and reliability of the resulting evidence.

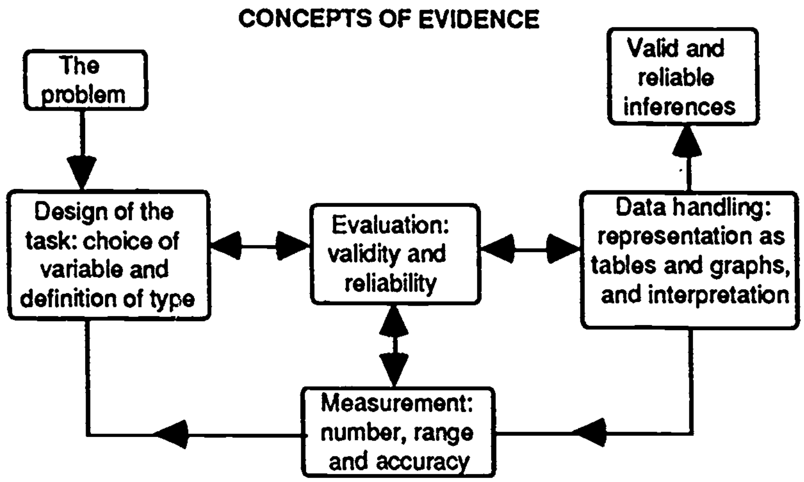

Fig. 2: Concepts of evidence in an investigation (based on Duggan *et al.*, 1994)

In terms of the title of this paper, the point we wish to make here is that progression relies on a definition of what is to be taught in order that it can be structured. The research suggests that procedural understanding as defined here is largely a 'black hole' in current science schemes.

Having established at least the bones of an argument which defines the procedural endpoint and outlines a possible content description, we must turn to evidence as to how that content might be structured and sequenced. Here we meet a fundamental problem. Since the 'content' has not been defined adequately, it has not been taught in any coherent fashion. Various of our skills and concepts of evidence are included in current science schemes, but as disembodied items rather than elements of a sequential structure. So if we look for evidence on pupil performance, we cannot say that it will give us a basis for curriculum sequencing, That performance may be a consequence of some skills or concepts of evidence being taught and others not, rather than a reflection of their inherent 'difficulty'. But we must start somewhere.

5. Procedural understanding - some research evidence

Evidence concerning pupils' performance on investigations in science has been accumulating over a number of years, beginning in the early 1980s with the work of the Assessment of Performance Unit, and continuing more recently under contract from the National Curriculum Council in the UK in the context of the UK National Curriculum (Foulds *et al.*, 1992). Investigations have been defined within the UK curriculum as being open-ended tasks in which pupils are required to develop their own strategy for a solution (see table 2 for some examples). Progression has been largely defined by the complexity of the task as described by the number and type of variables.

One of the key findings of the previous research summarised above was the extent to which performance on investigations depended on the interaction between conceptual and procedural understanding. The PACKS (Procedural and Conceptual Knowledge in Science) project was designed to investigate this interaction in the context of a number of investigations set in different concept areas and with a small sample of pupils (table 2) in the 9 to 14 age range.

Task	Description	Materials
Shrimps	Find out whether shrimps prefer light or dark conditions, or to be near the top or bottom of the water.	Tank of shrimps, containers of various shapes, pipettes, water, black polythene
Cool Drink	Find out how the thickness of the padding material affects how well a cool bag (for keeping a cool drink cold) works.	Beakers, measuring cylinders, supply of icecold water, thermometer, stopclock, supply of bubble wrap, fleece and foam sheet
Buggy	Find out how the speed of a battery-powered buggy depends on the diameter of the wheels and the weight of the buggy.	Battery-powered buggy, sets of wheels of 3 sizes, 100g masses, stopclock, metre rule, screwdriver (to change wheels)
Dissolving 1	Find out how quickly four different sugars dissolve in cold tap water and put them in order from the one which dissolves quickest to the one which dissolves slowest.	Small pots of four different sugars, stopclocks, scales, spatulas, spoons, graduated and ungraduated beakers, tap water
Dissolving 2	Find out how the temperature of the water affects the time sugar takes to dissolve.	Small pots of sugar, stopclocks, scales, spatulas, spoons, graduated and ungraduated beakers, thermometers, water (previously boiled and tap water available)
Forces 1	Find out how the type of surface affects the amount of pull needed to drag a brick along.	Half bricks into which hooks have been fitted, planks with a rough and a smooth side, a piece of corrugated card and a piece of carpet to fit on the plank, forcemeters, metre rules
Forces 2	Find out how the height of a slope (or angle) affects the amount of pull needed to move a brick uphill.	Half bricks into which hooks have been fitted, planks, forcemeters, metre rules

Table 2: The investigations used in the PACKS project (Millar *et al.*, 1994)

Given the restrictions of a short presentation, this paper will deal with one small but indicative example of this interaction. In the Forces 2 task (see table 2), pupils would, we hope, treat the height of the ramp (or the angle) and the force as continuous variables. We might further hope that they would draw a line graph to show the pattern in the data. This identification of the type of variable is an example of the linking of a number of skills and concepts of evidence into a strand of ideas that guides the investigation. It conjoins ideas about the nature and type of the variables, the range, number and accuracy of the measurements, the recognition and description of the pattern in the results and the controlling principles of reliability and validity to produce credible evidence. As we see from the data that follows, a variety of ways of treating the variables have been identified in the case study records.

Through a detailed case by case analysis of the interview and observation record, pupils were placed in one of the groups: 'label', 'order' and 'continuous'. The descriptors we have defined as follows:

Label — children treat any data, quantitative or qualitative as if it were merely a label such as 'red' or 'large'.

Order — children put their data into an ordered list, for instance, but show no understanding that continuous data must be placed on an interval rather than an ordinal scale.

Continuous — children treat the data in the scientifically correct manner, making the necessary links to produce a valid and reliable pattern from which to draw their conclusions.

The various alternative ways of identifying variables are outlined in Fig 3.

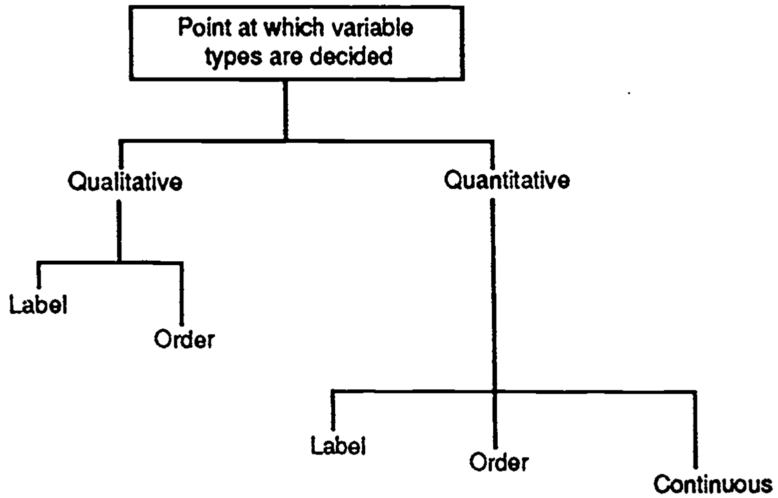

Fig. 3: A classification of variable identification and subsequent data handling (Millar *et al.*, 1994)

Table 3 shows how groups of children at various ages operationalised variables.

		Y4 primary	Y6 primary	Y9 secondary
Qualitative	Label	1		
	Order	6	2	
Quantitative	Label	3	1	
	Order	5	4	10
	Continuous	1	10	5

Table 3: Identification of the independent variable in the Forces 2 task

We see a progression with age towards identifying variables as ordered or continuous. But in secondary school, it seems as if pupils regress, in that many groups treated the data as an ordered set rather than as continuous[1]. We suggest that the introduction of more formal science has resulted in pupils becoming infected with a ritual approach to graphs in science. We make a further tentative suggestion, based on preliminary analyses of the data on the level of conceptual understanding in the area covered by the investigative task, that if pupils understand the nature of any continuous variable *and* have an understanding of the *particular* variable in the task (force in this case) and how it 'behaves' in relation to the height of the ramp, then they will operate in the 'scientific' manner which we ultimately expect (fig. 4). Whether or not this association is real, and if it is, whether it is causal or contingent, is under investigation.

1 The sample size is rather small however and caution must be exercised in making generalisations

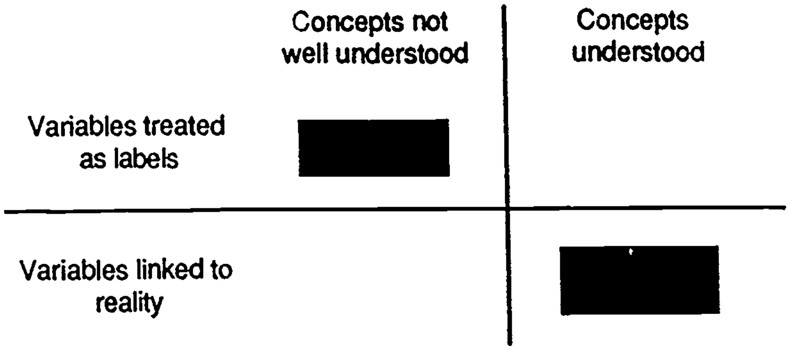

Fig 4: Possible progression in children's understanding of the identification of variables

Even more tentatively, it could be argued that the lack of a content description in current schemes of work is bound to lead to an incoherent experience for pupils and a reversion by teachers to the more familiar conceptual curriculum. They will tend, then, to see investigative work as the well trodden, and not necessarily efficient, means to conceptual understanding rather than, as we would argue, involving a knowledge base of its own with its own content and teaching techniques. It would not be surprising, if that is the case, for pupils to fail to make any coherent linkages in their procedural understanding and to fall back on a set of apparently acceptable rituals.

So our search for progression has some of its elements in place. The above findings suggest that a progression from seeing data as merely labels through to associating it with the physical situation is one possible strand. But until teachers are operating a scheme of work which incorporates procedural understanding and its associated content explicitly, the search for progression can only be tentative and provisional.

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