Procedural understanding in biology the thinking behind the doing (full text)

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Several developments in science education aim to improve pupils' ability to 'think scientifically'. This paper argues for the explicit teaching of the ideas that pupils need to 'think about' to do this; ideas related to the design of investigations and the collection, presentation, analysis, and evaluation of the resulting evidence — ideas which are important both for pupils who continue to study or work with biology and for all pupils to become biologically literate. This paper considers some of the concepts of evidence which are particularly important to biology, and discusses how and why the ideas could be taught.

Key words: Procedural understanding, Biology investigations, Scientific evidence, Biological literacy, Concepts of evidence.

The background

For many years, it has been recognised that science education should be more than just teaching about the 'things' that scientists know and have found out. It should enable pupils to 'think like scientists' and understand the 'nature of science'. Thus, recent science curricula have included elements of the procedures used in science as well as the theories of science. Attainment Target 1 (Sc1) of the Science National Curriculum in England and Wales is an example of how this is represented in a curriculum.

Various teaching and learning initiatives have been developed which have, amongst their aims, the development of pupils' understanding of how scientists work and the nature of science. Harrison (1998) includes, for example:

- Links with industry.
- Pupil Researcher Initiative.
- CREST award schemes.

Other curriculum developments aim to teach pupils higher-level thinking skills, argued to be necessary for problem solving in science. Such initiatives include the Somerset Thinking Skills; a course consisting of a series of modules designed to teach, discuss, and generalise specific concepts, skills, and strategies involved in problem solving (Blagg *et al*., 1988), though not specifically in a science context. The Cognitive Acceleration through Science Education (CASE) project is an intervention programme which stems from Piagetian psychology and is aimed at improving reasoning ability. Specific ideas of importance to science are taught through carefully sequenced interventions. Jones and Gott (1998) argue that CASE can help pupils to understand science because the content of CASE lessons specifically teach ideas that pupils need to be able to solve problems. Teachers' perceptions of the value of CASE particularly focus on the improvement in pupils' investigations: they understand the language of investigations and are more confident at handling data. Jones and Gott (1999) have suggested that CASE pupils' increased performance in GCSE might be attributable to success in Sc1 for just that reason.

At its simplest, it can be considered that for someone to be able to solve problems and judge evidence in science requires them to have an understanding of both the substantive ideas of science and a procedural understanding (Figure 1).

Problem solving in science is represented, albeit simplistically, as involving two kinds of understanding. In Figure 1, the left strand represents substantive understanding; how, for example, in a biological context, a knowledge of certain 'facts', such as the relationship between trophic levels in food chains and the role of glucose and oxygen in photosynthesis and respiration, can be synthesised into a broader substantive understanding of the importance of photosynthesis to life. Similarly, knowing how to use a point quadrat and the ability to identify plant species are skills that are necessary but insufficient in themselves to have a procedural understanding of how data collected using such sampling techniques can be used as evidence. When biologists solve problems both substantive and procedural ideas are used (Roberts and Gott, 1999; Gott *et al*., 1999a).

The facts and their synthesis to provide a substantive understanding of biology are generally recognised as being what is referred to as 'biology' (Roberts and Gott, 1999). In some biology textbooks these are the only ideas that are addressed (Roberts and Gott, 2000). This paper focuses on the procedural understanding of biology (which is often dismissed as just 'common sense' (Gott *et al*., 1999a)). Procedural understanding is referred to by Gott and Duggan (1995) as the 'thinking behind the doing'; what exactly is it that needs to be thought about to do science and, in particular, biology?

Concepts of evidence

The research at Durham University is based on the belief that there is a body of knowledge that underpins an understanding of scientific evidence. Certain ideas about the collection, analysis, and interpretation of data have to be understood before we can handle scientific evidence effectively. These ideas have been called the concepts of evidence. It is these ideas and their application and synthesis that constitute the 'thinking behind the doing'. Some pupils will pick up these ideas in the course of the traditional study of science, but many will not. Many pupils will not understand how to evaluate scientific evidence unless the underlying concepts of evidence are specifically taught (Roberts and Gott, 2000). If these ideas are to be taught, then they need to be carefully defined. What, exactly, are these ideas?

The concepts of evidence were developed by Gott and Duggan (1995) to describe the procedural understanding necessary for work in all science disciplines. However, at the time, the descriptors could be interpreted as being restrictive and more closely allied to lab-based investigations rather than being applicable to the many types of biology-based work, especially where relationships between naturally changing variables are investigated.

While asserting that biology-based investigations depend on a procedural understanding of the concepts of evidence, Gott *et al*., (website) more recently attempted to define the ideas in such a way that they could be much more readily applied to the range of contexts investigated by biologists. Different investigations place emphasis on different concepts of evidence. The latest definitions are summarised in Table 1.

An example of some concepts of evidence important in biology investigations

An investigation is an attempt to determine whether there is a relationship between the independent and dependent variables or between two or more sets of data. Investigations take many forms but all have the same underlying structure. Many of the concepts of evidence are relevant to all the sciences (such as how valid measurements are taken, evaluating the precision of measurements, or how secondary sources can be used to establish the validity of the results), but some have particular importance in biological contexts.

The design of investigations

What do we need to understand to be able to appraise the design of an investigation in terms of validity and reliability? Identifying and understanding the basic structure of an investigation in terms of variables and their types helps to evaluate the validity of data.

For instance, the independent variable is the variable for which values are changed or selected by the investigator to gauge the effect they may have on a dependent variable. In lab-based contexts the investigator might change the light intensity to find its effect on the rate of photosynthesis in Elodea. However, in an investigation to see if light intensity in a wood affects the size of leaves of dog's mercury, the investigator does not change the light intensity. S/he must select areas of different light intensity in the wood from which to sample leaves. The emphasis here has moved away from one of manipulation to one of selection in the context of variables that change naturally.

Fair tests and controls aim to isolate the effect of the independent variable on the dependent variable. Laboratory-based investigations, by our definition at one end of a spectrum of a range of valid designs, involve the investigator changing the independent variable and keeping the value of all the control variables constant. By way of example, in the Elodea photosynthesis investigation (above), attention is given to maintaining a constant temperature throughout, by thermally insulating the plant from the light source. The control variables are manipulated to maintain their constant value. Such designs are often referred to as a 'fair test'. At the other end of the spectrum are 'field studies' where many naturally changing variables are measured and correlations sought. For example, an ecologist might measure many variables in the woodland habitat that might affect the dog's mercury's leaf size, such as the height of the plant, the density of the plants and surrounding vegetation, pH of the soil, leaf-eating insect activity, the age of the plant, availability of water, and the maximum and minimum temperatures at the site. Having collected the data, correlations might be sought between one of the variables, such as light intensity, and the dependent variable, leaf size. To do this, the effect of any of the other variables on the size of the leaf has to be 'controlled' for, by only comparing data that has similar values of the other variables. Validity is ensured but without the direct manipulation of the variables.

In between these extremes are many types of valid design which involve different degrees of manipulation and control. For instance, in trials of fertiliser on tomato plants conducted in the field the investigator would change the concentration of the independent variable but would not maintain constant environmental conditions around the plants. Validity is ensured by all the plants being subjected to the same conditions, even if the values of the variables were not kept constant.

Fundamentally, all these investigations have a similar structure; what differs are the strategies to ensure validity. The mantra of 'everything must be kept the same' is not applicable in all biology contexts.

Control groups are used to ensure that any effects observed are due to the independent variable(s) and not some other unidentified, and therefore uncontrolled, variable. So, in a drug trial, patients suffering from, say, hayfever are divided into an experimental group who are given the drug and a control group who are given a placebo or no drug. The results from each group are compared to ensure that any change in the dependent variable, the severity of symptoms, is due only to the application of the drug and not some unexpected variable, such as a drop over the trial period of the prevalence of the allergen. For the most part, in most physics and chemistry contexts the control variables can be identified. The idea is of importance in biology-based investigations because of the complexity of biology: there are so many variables that might affect the dependent variable that identifying all of them is not always possible. The selection of the groups involves understanding of the ideas that underpin **sampling**; in this case a consequence of variation in the population, which is of particular importance in biological contexts.

Teaching for procedural understanding in biology

Why?

Several reasons have been put forward as to why biology teaching should aim to develop pupils' procedural understanding.

The first is to do with the **aims of biology education**. As has been argued in Roberts and Gott (1999), it is clearly important that biology education should prepare some pupils for becoming working biologists, whether in a university or research centre or in an 'applied' field such as medicine, a biology-based industry, or an environmental organisation. A procedural understanding is necessary for this work (Roberts and Gott, 1999; Gott *et al*., 1999). Biology education should have as one of its aims the development of biological literacy in all our pupils, so that everyone can make decisions about biological issues. Ideas to do with evidence are central to this. A biologically literate person should regard controversies in areas such as pollution, conservation, or medicine as something which it is possible to understand sufficiently well to hold an informed opinion; for instance, whether to vaccinate children, whether to undergo a medical treatment, whether to live near a nuclear power station or whether to be concerned at the reported drop in fish stocks. It is logical that a procedural understanding is necessary to meet these aims.

Reiss *et al*., (1999) contend that a curriculum to met these aims should be clearly differentiated into elements that meet each aim. Both of these objectives can be met by teaching a curriculum which reflects what professional biologists know and do (Roberts and Gott, 1999), since the concepts of evidence are an important part of the 'thinking' of biologists. Both substantive and procedural ideas are needed for further work in biology and for biological literacy.

The second is to do with the **pupils' perceptions of biology** in the curriculum. Biology is a diverse active science. However, the diverse nature of biology as a discipline means that a range of approaches are used to gather evidence: tightly controlled, lab-based physiology investigations; plant growth experiments; and ecological surveys, to suggest just a few. Biology education should reflect this range. Many real biology-based topics of interest to pupils involve understanding concepts of evidence such as the size and representativeness of the sample, the concept of control, and the idea that correlations do not imply causality, in addition to the ideas of importance in any other investigation. Pupils need to be taught the ideas of importance to a wide range of biology investigations, not just lab-based manipulations. Many teachers and authors have noted their concern that a restricted repertoire of lab-based manipulative investigations have come to dominate current teaching (Watson *et al*., 1999) and this may skew pupils' perceptions of biology. Recent comments from A-level students doing fieldwork suggested that they found the investigations interesting and motivating. Comments such as 'It's interesting because the results aren't fixed,' and 'You can see how science answers questions in the real world,' are indicative of their attitude.

Thirdly, the **National Curriculum** in England and Wales has included both substantive and procedural ideas since its inception. Sc1 assessments can only be enhanced by pupils understanding the concepts of evidence. Some pupils recently described their current practice for investigations as 'carrying out the ritual, because we always do it this way'. They were unable to describe why they were doing what they did; there appeared to be no 'thinking behind the doing'. Reiss *et al*. (1999) point in the National Curriculum to the 'over-emphasis on content which is often taught in isolation from the kind of contexts which could provide relevance and meaning'. By teaching ideas important to a range of biological investigations, greater 'relevance and meaning' might be provided for the rest of the curriculum.

How?

The concepts of evidence are a satisfactory, if not necessarily complete, description of what needs to be understood to develop procedural understanding. At secondary school and BA Ed (primary) level in Durham (Gott and Johnson, 1999), we have found that the concepts of evidence are ideas that can be taught, just as the substantive ideas of genetics, classification, and physiology can be taught.

The National Curriculum places procedural ideas firmly in the context of practical work. Nott and Wellington (1999) note that the majority of investigations take place in the context of assessing rather than teaching Sc1. The ideas that are emphasised, unsurprisingly, are those of investigation design and looking for patterns and relationships. Time and resources often limit the scope of school investigations. Therefore, many of the concepts of evidence, particularly those important to the range of biological contexts, are rarely addressed in the majority of school practicals, but they are, nevertheless, important for pupils to understand if the aims we identified are to be met. How, then, could they be taught?

Roberts and Gott (2000) argue that procedural ideas can and should be taught just as the more traditional substantive ideas are taught. For example, pupils are not expected to understand the importance of the circulatory system or the role of natural selection in evolution without explicit teaching; we argue that the concepts of evidence also need explicit teaching if pupils are to develop a procedural understanding. Similarly, just as both practical and non-practical activities can be used to teach the substantive ideas, both approaches can be used for procedural ideas. The choice of activity can be varied according to the idea being taught, the class, and the pragmatics of time-tabling and resourcing. (By comparison, CASE teaching methods are tightly specified and may not suit all pupils (Jones and Gott, 1998).) Table 2 (from Roberts and Gott, 2000) outlines the activities that could be used.

In a recent survey, secondary school science texts were analysed to determine how the concepts of evidence were presented (Roberts and Gott, 2000). Implicit references to such procedural ideas were the norm and occurred almost exclusively in the context of practical work. Explicit mention was very rarely made to the procedural ideas. Tamir *et al*. (1998) have shown that explicitly teaching procedural ideas to pupils helps their understanding. If procedural ideas are so rarely explicitly mentioned in texts, what support is there for teachers and pupils?

Recent publications have addressed teaching Sc1. Significant amongst these are:

- The AKSIS resources (Goldsworthy *et al*., 1999, 2000) which have been produced specifically to help teachers develop strategies to teach science investigations. The writing team claim to be teaching ‘thinking strategies’ (Goldsworthy *et al*., 2000), but many of their activities’ ‘Learning Objectives’ refer to the specific ideas that need to be taught.

- Science Investigation packs (Gott *et al*., 1997, 1998, 1999b) have been developed at Durham as photocopiable resources for explicitly teaching and assessing procedural ideas using both practical and non-practical approaches. These specifically emphasise how these ideas can be used in a range of biological contexts and which are often not made explicit in the teaching of Sc1.

Questions for the future

There are still many questions about teaching for procedural understanding that remain to be answered. The answer to these questions should impact on curriculum developers and our assessment procedures as well as the way in which we teach for procedural understanding.

- How should the ideas be sequenced to ensure progression? (Harlen (2000) suggests a sequence appropriate to primary science and identifies a need to reflect on the emphasis placed on different procedural ideas.)
- Is progression in biology the same as in the other sciences?
- Can teaching for procedural understanding be shown to ‘work’ in terms of pupils’ future work either as biologists or in their scientific awareness of issues such as BSE, sustainability, etc.?
- How best can procedural ideas be taught to empower pupils and make them biologically literate?

These questions need to be the focus of further research.

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Table 1 A summary of the concepts of evidence (from Gott *et al.* (website)).

Major ideas to do with	A summary of the underpinning procedural ideas
Instruments	All instruments rely on an underlying relationship which converts the variable being measured into another that is easily read. Do they: • measure what is intended and are thus valid? • give readings which can be repeated and are, therefore, reliable? • give an accurate reading?
Single measurement	What do we need to understand about a single measurement to be convinced that it is valid and reliable? Here we are concerned with the relationship between the choice of the instrument and the required scale, range of readings required, and their interval (spread) and accuracy. The ideas presented here subsume all the ideas in the previous section on instruments.
Design of an investigation	What do we need to understand to be able to appraise the design of an investigation in terms of validity and reliability?

Patterns and relationships	Having established that the measurements and the design of an investigation are reliable and valid, what do we need to understand to know the relationship between one variable and another?
Data from others	How do the results of an investigation compare with other data from other sources? These ideas are all concerned with validity.
Bias	Finally, in reality if we are faced with a piece of evidence and we want to arrive at a judgement then other factors will come into the equation, such as the credibility of the investigators, their status, power structures and bias.

Table 2 An outline of the activities that could be used to teach for substantive and procedural understanding.

	Practical activities which might include:	Other 'non-practical' activities which might include:
Substantive ideas	• observations of objects or events and their classification • illustrative practicals in both field and lab • 'discovery' learning and enquiry practicals	• didactic teaching • active learning using text • discussion • presentations • the use of models
Procedural ideas	• whole and parts of investigations in both field and lab • illustrative practicals in both field and lab • basic skills practicals	• didactic teaching • active learning using text • discussion • presentations • use of second hand data • evaluating investigations

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