Biology: the ultimate science for teaching an understanding of scientific evidence

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Abstract

Recent school science curriculum developments in many countries emphasise that scientists derive evidence for their claims through different approaches; that such practices are intimately bound up with disciplinary knowledge; and that the quality of data should be appreciated. This position paper focuses on the role of Biology to understand evidence, an essential component of ‘scientific practice’. Biology is an empirical science, using evidence to support claims. Yet biological practice is diverse – including, *inter alia*, observations, lab-based experimentation, field trials, ecological surveys, randomised controlled trials – so how can we teach, within the time-constraints of the curriculum, to help pupils really understand about evidence in biology? In this paper biology is shown to be the ultimate context for teaching about evidence and ‘scientific practice’. The paper draws on a body of research that presents an understanding of the validity of data as a set of conceptual relationships, shown on a concept map. Using examples from biological practice, the paper shows how teachers can illustrate the application of the network of all these ideas and their inter-relationships within the biology curriculum, to help pupils develop the necessary ‘thinking behind the doing’. The paper explores ways in which this understanding is inherently related to underpinning disciplinary ideas of biology.

Keywords: biological practice, concept map, concepts of evidence, investigations, practical work

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1. Introduction

The science curricula in many countries now include not only 'the products' of science - substantive facts, theories and laws, sometimes referred to as the content knowledge (e.g., OECD, 2013) - but also "the processes and characteristics of the scientific enterprise" (Roberts, 2011, p. 12). A common feature is to "understand the methods by which science derives the evidence for the claims made by scientists, [and] to appreciate the strengths and limits of scientific evidence" (Millar & Osborne, 1998, p. 2004). Large-scale international science assessments such as PISA (OECD, 2013) and TIMSS (Jones et al., 2013) also reflect this curriculum emphasis of understanding 'scientific practice'.

Roberts & Johnson (2015) report that many international curricula now, in addition to the vital substantive knowledge-base of science, include an understanding of the diversity of empirical practice; the important relationship between substantive knowledge and this 'doing' aspect; and the importance of pupils being able to use their understanding to evaluate empirical work and reason with evidence as well as being able to carry out practical work. Roberts & Johnson (2015) put forward a detailed case for how curricula might be framed and how teaching may be structured to support an understanding of evidence which underpins 'scientific practice'. This position paper will build on their work and will argue that biology as a subject, due to its nature, provides an ideal opportunity for teaching about scientific evidence.

2. Scientific practice

Scientific practice is not the same as 'school science practice'. In school science we aim to teach about scientific practice, but what we enact in the school curriculum - often but not exclusively through our use of practical work – is, understandably, not necessarily what scientists do in their practice. This distinction is important. Scientific practices vary across science disciplines and also within them, and not only because of the specific subject knowledge required. How research is designed and conducted to solve different problems varies according to what is being investigated (for instance, using different approaches such as tightly controlled lab-based research; or the observation of phenomena; in field surveys which suggest links between factors; or in Randomised Controlled Trials (RCTs)) each with concomitant effects on the validity of the data and the strengths of the claims made. Research may also differ in, *inter alia*, the equipment employed, the manual skills required and the specific techniques selected. This presents a challenge to curriculum developers and teachers. How can this diversity of scientific practice be taught and evidence understood within the limitations of a school curriculum?

2.1 Chains and nets

Research into real-world practice can give us some insights that can help to frame the problem. Kinchin and several colleagues over the years have extensively researched expertise and their analysis is represented in Figure 1. They have shown that expert practice, despite appearing to consist of linear chains of practice, is underpinned by complex nets of ideas. The understanding represented by the nets makes the difference between competent enactment of a particular practice and the ability to make evaluative decisions about the practice. Experts therefore draw on a complex net of underpinning ideas to make decisions as they practice which may make it appear deceptively 'straightforward'; and yet, crucial to this is the networked understanding that enables them to make informed and evaluative decisions.

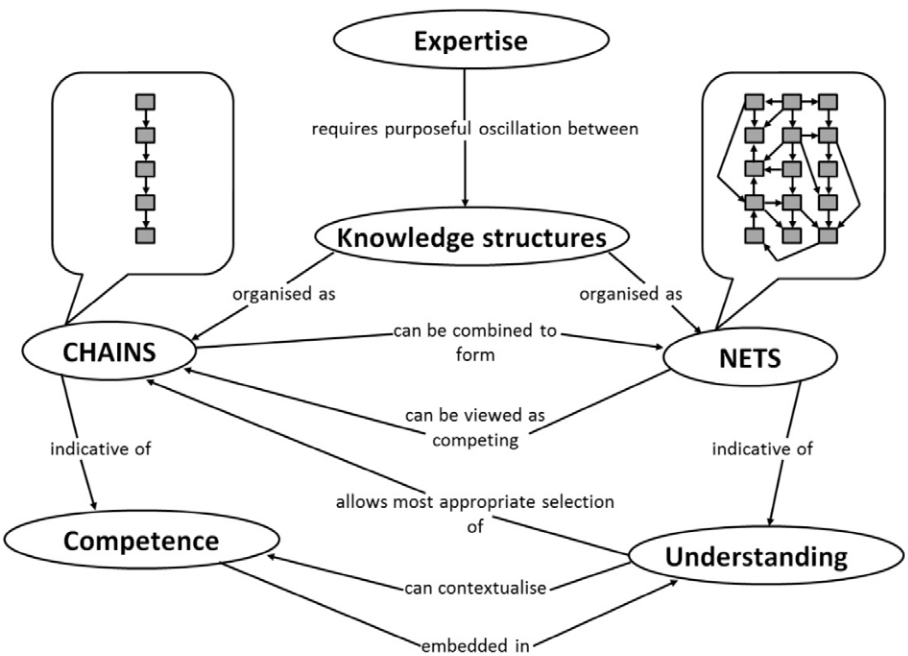

Figure 1 A dual-processing knowledge structures perspective on the nature of expertise (from Kinchin & Cabot 2010:161).

In empirical sciences there are, of course, myriad practices which endeavour to collect valid data – and biology, in particular, encompasses a very diverse range – which could each be represented by chains, but the importance of Figure 1 is that it draws attention to the understanding, represented by the nets, that underpins expert practice. Roberts (2016) argues that in scientific practice, it is this understanding of evidence, the 'thinking behind the doing', that enables evaluative decisions to be made to optimise the quality of the data collected.

While school curricula may not aim to develop expertise in school pupils, we do expect pupils to be able to "develop *understanding* of the nature, processes and methods of science, through different types of scientific enquiry that help them to answer scientific questions about the world around them … (and) develop their ability to evaluate claims based on science through critical analysis of the methodology, evidence and conclusions" (as stated in the National Curriculum for England (DfE, 2014, pp.3-4, emphasis added), which is not atypical of other countries' curricula. Figure 1 therefore has implications for what and how we teach pupils to meet these specific curriculum aims.

Practical work in science classrooms is often represented as chain-like practice – as relatively linear processes to be followed, recipe-like, with few decisions to make (Abrahams & Reiss, 2012). Of course, if the purpose of the practical is to illustrate some substantive idea or phenomenon (such as osmosis or photosynthesis) then following a protocol that someone else has already developed specifically to reduce any uncertainty so that the substantive ideas are clear may be useful (most particularly if the substantive idea has already been introduced and the practical is used to help reinforce the learning (Hodson, 1992; Millar, 1998)). If the purpose is to illustrate, by exemplification of different approaches, the diverse range of practices and protocols in science, or to develop manual skills, it too can arguably be useful. However, there is evidence that just *doing* a practical does not always result in meaningful learning (Abrahams & Reiss, 2012) and research shows that, for the most part, it does not provide a route to understanding evidence (Glaesser et al., 2009) which is the focus of this paper.

Many science curricula are written as 'descriptions of practice' to guide staff and pupils in doing investigations, breaking down the complexity of investigating into sequential processes such as 'planning', 'collecting data', ‘analysing’ and ‘evaluating’ but many pupils still struggle to design their own investigations (which Glaesser et al, 2009, show requires that they understand evidence) other than by close mimicking of ‘unwritten recipes’ of chain-like procedures with which they are already familiar (Roberts & Gott, 2006). Pupils seem to resort to similar chains of practice since they have not developed an understanding of evidence which can be applied to solve problems.

In short, chain-like practicals (the left of Figure 1) have their place in science teaching but are not an efficient or systematic ways to develop the understanding of evidence (the right of Figure 1) that underpins scientific practice as specified in the curricular aims. Lunetta et al. (2007, p.433) (using the term ‘laboratory’ synonymously with ‘practical work’) have suggested that “Much more must be done to assist teachers in engaging their students in school science laboratory experiences in ways that optimise the potential of laboratory activities as a unique and crucial medium that promotes the learning of science concepts and procedures, the nature of science, and other important goals in science education”. Practical work in the curriculum is necessarily constrained by time and opportunity. Perhaps, instead of exposing pupils to a limited selection of chains of practice, and hoping that that they will understand scientific practice almost ‘by osmosis’, if a curriculum was framed in terms of understanding the ideas about the quality of data that underpinned such practice, and practical work was selected explicitly to support this understanding, there could be an efficient way to meet the curriculum aims.

2.2 Concept map

With this in mind, Roberts and Johnson (2015) have attempted to show the ‘thinking behind the doing’ of science encompassing most if not all of ‘scientific practice’ in schools as a concept map (Figure 2) which focuses on the quality, or validity of the data. Understanding can be represented on concept maps, where both the ideas and their inter-relationships can be shown (Novak & Cañas, 2007). This map centralises the question of the quality of the data since the degree of confidence in the validity gives it weight as empirical evidence for a claim. Understanding the quality of data is an essential component of scientific practice. Figure 2 is their attempt to articulate the net of ideas underpinning scientific practice, equivalent to that on the right of Figure 1. The concept map is based on the concepts of evidence (Gott et al., n.d.) and illustrates how scientific practice is underpinned by a conceptual understanding: an understanding about the quality of data. The map focuses on the validity of data generated in carrying out scientific investigations. The quality of empirical data is a central component where the ideas provide the foundation for understanding other aspects of scientific practice. Space does not allow elaboration upon these contingencies here but the reader is referred to Roberts & Johnson (2015) who discuss the implications of the map to teaching the Nature of Science and argumentation.

Viewing scientific practice as having a conceptual knowledge-base to be understood, rather than a series of procedures to be practiced, represents an ontological shift in its characterisation, which has implications for curriculum developers, teaching and assessment. As a knowledge-base, the ideas and understanding of evidence can be specified in a curriculum and explicitly taught and assessed, just as the substantive ideas of science are.

Broadly speaking, Figure 2 has two interrelated sides. On the left is thinking about variables and on the right thinking about measurement. The relationships between these ideas are the basis for decision-making ('the thinking behind the doing'). Since the arrows represent the conceptual links between the ideas, there is no implied sequence in the map and it is not a 'flow diagram'. The map shows the understanding behind the whole of 'scientific practice' in schools. It is important to note that some practices focus on just some areas of the map.

Roberts and Johnson (2015) have exemplified how the ideas in the map are used to make decisions when collecting data in both lab-based and ecological fieldwork; significantly the map does not privilege any particular approach to scientific practice (and this will be expanded on later) but shows the understanding regardless of approach. In terms of validity, there is no distinction between approaches (such as an 'experimental approach' or an 'observational' or 'historical approach') to finding patterns in data (Cleland, 2002). The key issue is what is appropriate depending on the circumstances.

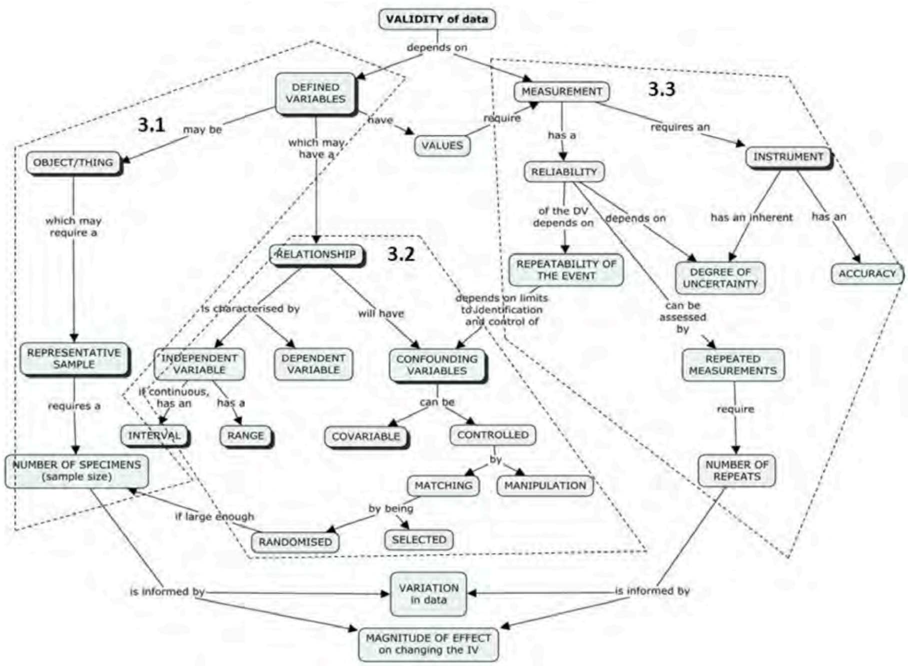

Figure 2 A concept map of the 'thinking behind the doing' of scientific practice (based on Roberts & Johnson, 2015:348). Concepts directly informed by substantive knowledge are highlighted with a shadow on the box. Concepts addressed in sub-sections 3.1, 3.2 and 3.3 of this paper are identified.

From the curriculum perspective (to understand evidence, vital to 'scientific practice') with the aims of both being able to investigate and evaluate others' work, it is worth noting that the same understanding is employed when evaluating scientific practice as it is when collecting valid data. Roberts & Johnson (2015) illustrate how an investigator uses these ideas and their inter-relationships to make decisions while conducting both lab-based and ecological investigations; while a case study (Tytler et al., 2001) - about sampling emissions from a cement-works when it changed the fuel burnt in its furnace - illustrates how the same ideas are important when evaluating scientific practice, in this case in an outdoor context. Essentially, when investigating - in the lab or in the field - decisions have to be made with an eye on the **validity of the data**[2] to be collected and, when evaluating, the same understanding is used to interrogate the data.

[2] Terms shown in bold in the account are ideas of evidence represented on the concept map (Figure 2).

In investigations into potential relationships between variables (just one type of scientific practice, but one which employs all the ideas shown on the map and hence used to illustrate the map), **variation in the data** (relative to the **magnitude of the effect** of the change in the independent variable) is key and this is affected by many factors which are shown (from left to right) on the concept map: factors to do with variation in the variables being investigated; in the ability to manipulate and control variables; and in the uncertainty of the measurement. Roberts & Johnson (2015, p. 359) illustrate how "decisions when investigating are based on nuanced application of these ideas, involving mental juggling as juxtapositions and contingencies are considered according to context". Understanding and applying these ideas is a far cry from the routine 'recipes' of many chain-like school practicals and employs higher-order thinking to meet the aims of the school science curriculum.

So how can this understanding be developed and why is Biology the ultimate science for addressing this? This understanding of the quality of evidence is inextricably linked with substantive understanding (the 'subject matter' of science – its facts, models, laws and theories) and those concepts directly informed by substantive knowledge are highlighted with a shadow on the box in Figure 2. It is the substantive 'subject matter' of biology that provides opportunities for a sophisticated understanding of the map to be readily taught (discussed later). The map emphasises the intimate integration of substantive knowledge with scientific practice. Neither stands alone, each is only as good as the other. The soundness of substantive knowledge depends on the quality of the originating data as evidence. They are inextricably bound (as discussed further in Roberts & Johnson (2015) and Johnson & Roberts (2016)).

3. The nature of biology and scientific practice

The variables of science are the creation of the substantive knowledge of the discipline. As Lederman et al. (2014, p. 68) state, investigators "need to have specific knowledge that has been melded into some curious pattern or question". Any limitations in understanding of pertinent substantive ideas affects what can be observed (Haigh et al., 2012). Substantive knowledge is fundamental to scientific practice. The many different approaches to research and the resultant validity of the data and strength for a claim can be viewed as the consequence of differences in the nature of the variables involved and their measurement in any investigation. The degree to which variables can be isolated and their values manipulated, and the amount of variation in a defined variable influence how relationships are sought and the strength of any resultant claims. This is true of all scientific investigations, yet in the majority of school physics and chemistry investigations (typified as involving variables with very little variation, that can be easily manipulated and isolated and with well-established instruments with relatively little uncertainty) the opportunity to develop the understanding represented by the map may be missed. However, the nature of biology's 'subject matter' provides the ultimate context to develop an understanding of evidence, as represented by the map.

Biological practices vary and include *inter alia* tightly controlled lab-based research; the observation of phenomena; field surveys which suggest links between factors; and Randomised Controlled Trials (RCTs). These diverse approaches have concomitant effects on the validity of the data and the strengths of the claims made; all employ the underpinning understanding of evidence represented on the concept map. The map centralises the question of the validity of data since the confidence in the validity in any research practice gives it weight as evidence for a claim – it is this that all biologists are striving for, regardless of their approach, and is at the forefront of expert researchers' thinking whether they are researching in a lab or the field, doing 'classical experiments' or 'observational study' (Gray, 2014). These diverse practices can be related to the nature of biology's variables, and it is the nature of biology's variables and the resultant diversity of practice that allows *all* the ideas on the concept map to be explored in a biology curriculum. Working from left to right across the concept map (Figure 2) these will be exemplified.

3.1 Variables

The **defined variables** of biology include those that are the focus of physics and chemistry – length, mass, time, energy, substance, rate of chemical change etc. – but also include many with larger inherent variation, for example 'a species'; 'a community'; varying 'environmental factors'. To be able to investigate variables like these, whatever role they have in an investigation, a **sample size** will be required and the validity of the data acquired and claims made will depend on the **representativeness** of the sample. This is not to suggest that the inherent variation in many of the variables in biology is a problem! These variables are the subject matter of biology and are often the focus of biological practice. The map points to how, if there is variation, this must be taken into account when understanding evidence. If there is little variation in the variable, such as in work with isolated genes or when clones are being used, the issue of variation has been reduced so much that a small sample size (sometimes reduced to an individual) is going to provide valid data, as it does in many chemistry and physics practices where, for instance, 'quality control' processes eliminate any potential cause of variation, e.g. in the purity of a substance, and therefore the opportunity to teach these important ideas about evidence – shown on the left of the map – may be overlooked. But in many instances in biology, such as work involving variables such as 'holly bushes', 'flow rate of a stream' or 'boys', the inherent variation will affect the validity of the data unless a sufficient sample of readings 'captures' the variation in each. In school practice the collection of large class datasets in such circumstances in biology provides an opportunity to teach explicitly about these ideas.

3.2 Relationships

In an investigation where a **relationship** is sought between variables (identified as the **independent** and **dependent variables** on the map; but, as Roberts & Johnson (2015) state when explaining the map, their terminology does not imply a causal link), the ability to isolate other potentially **confounding variables** affects the validity of the data. The identification of confounding variables absolutely draws directly on substantive knowledge and is limited by that knowledge. There has to be a reason for deciding upon a particular variable, if only because it might be relevant. The potential effects of confounding variables must be **controlled** in some way to isolate any relationship between the variables being investigated. But the nature of many of biology's complex variables can make this difficult. For instance, in research involving individual organisms, each organism is composed of a complexity of other, inseparable, **co-variables**. Even at a simpler level, variables such as substrate size and oxygenation of water in a stream are co-variables associated with the velocity of the water. It is often only in 'experimental' conditions that variables might be isolated and **manipulated**. The manipulation of variables is a means of control so that the **values** can be fixed at a constant value so as to isolate the relationship being investigated. In field trials, control can be achieved even if the values are changing over, say, 24 hours, by manipulating the experimental conditions so

that all specimens are subject to the same conditions (Roberts, 2001).
The inability often to isolate variables in biology means that other approaches to deal with the effects of confounding variables must be used, so that the relationship can be explored but with consequent effects on the **variation in the data** collected. In ecological surveys, for instance, the values of the variable 'aspect of slope' can only be **matched** by **selection** of sites with similar values; and in the formation of comparisons groups samples may be matched on several key characteristics e.g. patients selected with similar conditions such as being of a similar weight, age and medical history. In randomised controlled trials (RCTs), subjects are assigned to treatment groups by a **random** process. With a large enough sample size it can be assumed the multifarious confounding variables will 'even out' so the only difference overall is the treatment applied to one group and not the other. Roberts & Johnson (2015) and Johnson & Roberts (2016) provide further exemplification.

3.3. Measuring variables

The concept map shows that another source of variation in the data is due to **measurement** issues. Measurements in biology can be both quantitative and qualitative. The concept of measurement (although often referred to as 'observation'; see, for instance Gray, 2014) can also be applied to categoric variables, where qualitative descriptions are the values. Here, the measurement entails the recognition of the defining features of the variable (for instance, a species), with the substantively-informed discernment of the observer acting like an instrument; and with an element of uncertainty introduced if identification is wrong. The quality of the data and the strength of any claim made from it are affected by **variation in the data.** There is a **degree of uncertainty** in all measurements but in some situations in biology this can be quite large (in comparison with many situations in the physical sciences) and this provides an opportunity to teach about the effect it has on the variation in the data explicitly. In situations where the variation caused by the nature of the variables is relatively low, the uncertainty associated with measurement can contribute significantly to the variation in the data. Such is the case in many physics and chemistry-focused investigations and then much attention is paid to improving the measurements to reduce the variation. In some situations in biology where the variation in the data, due to the nature of the variables, is large in relation to the effect of changes in the independent variable, the focus of the efforts when collecting data may be relatively less on improving the measurement. For example, ACFOR scales based on estimates of relative abundance of a species in ecology have acknowledged uncertainty but pragmatic reasons may influence their adoption in situations where the other causes of variation in data are so large. Examples like this, in biology teaching, provide opportunities to explicitly address important concepts of evidence associated with measurement that affect the quality or **validity of data.**

The nature of many of biology's variables are complex, often involving inherent variation i.e. within a species, requiring sampling. Many variables cannot be easily isolated one from another and cannot always be manipulated by the investigator. All of these characteristics, as well as the quality of any measurements, result in variation in the data, which in turn affects the strength of the resultant claim and our explanation of any potential relationship found: causation may not necessarily be claimed. Concluding that data do show a relationship is one thing, explaining that relationship is another matter. The relationship may be causal, may be an association due to a common cause or may simply arise by chance. Substantive ideas will be used here to consider the question of causality and the relative merits of competing theories.

As biologists, we know that our biological practices must take account of the nature of the variables we are working with and this has resulted in a diverse range of approaches in biology to obtaining data that is as valid as possible. Biology provides the ideal opportunity to teach pupils about all the ideas required to understand evidence, as represented in Figure 2.

4. Teaching about evidence in biology

The significance of the concept map (Figure 2) is that it shows that there is a knowledge-base (the concepts of evidence) to understanding the quality of data that underpins scientific practice (the right of Figure 1). Roberts & Johnson (2015) point to the concept map (Figure 2) having implications for research in science education, policy, curricula and school practice. It is the last of these that will now be considered briefly.

Research with undergraduates (see for instance Taylor & Meyer, 2010; Wilson et al., 2010) shows that aspects of scientific research expertise indicative of network thinking are poorly developed as a result of school curricula and practice, wherein pupils often carry out chain-like practicals and scientific practice is framed in terms of descriptions of practice rather than as a set of ideas. The concept map points to an alternative way to meet our curriculum aims of understanding scientific practice: it frames scientific practice as having a conceptual basis – a set of ideas that can be explicitly taught and assessed, using a range of engaging pedagogical activities, just as we teach the more familiar substantive concepts such as photosynthesis, succession or adaptation. As with other learning, both practical and non-practical teaching activities can be used, with the selection made based on the best route to the learning outcomes (of understanding the ideas and the relationships in the map).

Support for activities suitable for school pupils that focus on these often-ignored ideas is available (see Gott et al, 1997; 1998; 1999; Gott et al, n.d.; Roberts & Gott, 2002; Roberts & Reading, 2015) but a teacher needs to be alert to the possibilities.

In biology, many opportunities to teach this understanding explicitly present themselves due to the nature of biology. All the concepts discussed in this paper have been taught explicitly by the author and colleagues; and key points to be considered when teaching to develop this understanding from this experience are summarised in Roberts & Reading (2015). They suggest that pupils should be introduced to, and develop a secure understanding of, elements of the map through activities where the understanding of evidence ideas is the focus of the teaching activity and the pupils' learning. Trying to learn about evidence when the focus of the teaching is on substantive ideas seems not to work – explicit teaching that focuses on evidence means that pupils aren't distracted from this by the more familiar subject matter. Once pupils have developed that understanding then applying it in more sophisticated biological contexts is possible. As Roberts & Reading (2015, p.38) state: "The challenge is therefore:

1. to plan a curriculum that enables a progression in pupils' understanding of the ideas of evidence;
2. to 'map' this across the progression planned for the substantive content and the school's teaching sequence;
3. to include practical activities within this sequence which have as their focus the illustration or application of the ideas of evidence."

In terms of sequence, we focus on different sections of Figure 2 in our teaching, starting with variables with little inherent variation in contexts where values can be manipulated (the familiar 'fair testing' wherein control variables' values are 'kept the same') and then considering how a valid design might be established in situations where they can't, such as field trials (where many values – such as temperature - are not held at a constant value but are allowed to change across all treatments) to ecological selection of sites matched for key variables. Issues to do with the quality of measurement are then addressed so that students get an understanding of variation in the data before other sources of variation, such as in the sample, are introduced. We have worked with teachers who have decided to introduce pupils to ideas about evidence as a separate 'module', often at the start of the year, so that the ideas can be repeatedly addressed within practical work in the other more familiar substantive modules. Others have decided to introduce pupils to ideas explicitly as they arise through the substantive work they have planned – short 'nodules' of teaching about evidence as the opportunity arises.

Since this approach represents a conceptual basis for understanding evidence, decisions can be made about the sort of activities best used to teach the ideas. As with the substantive ideas of science, these can involve using both practical and 'non-practical' opportunities. Practical work is important in developing this understanding – during open-ended investigations pupils can make these decisions for themselves and see the effect of their decisions on the quality of the data and recognize this affects the strength of their claim. In genuinely 'open-ended' contexts where pupils are not focusing on getting 'the right answer' they can focus on the 'trade-offs' between sections of the map and their practice is characterized by trials and iterative working. We have also found that students learn lots from discussion involving their own and others' data. Having generated their own data, pupils seem better able to understand the sources of variation in it. The importance and meaning of simple statistical tests and graphical forms of data presentation can then be appreciated more in our experience. Having grappled with 'messy data' and discussed how best to get meaning out of it students appear to be in a better position to understand the conventions employed in handling data and presentation.

5. Conclusion

Since the concepts of evidence are validated across all scientific disciplines (Gott et al., 1999; Roberts & Gott, 1999) they can be taught in all science subjects. Chemistry's and physics' focus on variables that have such little variation means that, in school science at least, the ideas of representative sampling can usually be ignored. School chemistry and physics are usually studied in situations where variables can usually be isolated and manipulated and their investigations use well-developed and precise measuring instruments which means that learning opportunities have to be specifically developed to draw learners' attention to all the ideas of evidence on the map. However, the nature of biology and the topics addressed in school biology curricula enable *all* the key elements of the concept map to be readily addressed. The nature of biology's variables and the diverse practices employed and taught about in school biology curricula suggest that biology is the ultimate science to readily develop this understanding of all the ideas on the map.

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