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English secondary students' thinking about the status of scientific theories: consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world - or just '*an idea someone has*'.

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Abstract

Teaching about the nature of science (NOS) is seen as a priority for science education in many national contexts. The present paper focuses on one central issue in learning about NOS: understanding the nature and status of scientific theories. A key challenge in teaching about NOS is to persuade students that scientific knowledge is generally robust and reliable, yet also in principle always open to challenge and modification. Theories play a central role, as they are a form of conjectural knowledge that over time may be abandoned, replaced, modified, yet sometimes become well established as current best scientific understanding. The present paper reports on findings from interviews with 13-14 year olds in England where target knowledge presents theories as "consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world". Student thinking reflected a two-tier typology of scientific knowledge in which largely unsupported imaginative ideas ('theories') became transformed into fairly definitive knowledge (such as laws) through relatively straightforward testing. These results are considered in relation to research into intellectual development which indicates that effective teaching in this area requires careful scaffolding of student learning, but has potential to contribute to supporting intellectual development across the curriculum.

Keywords:

nature of science (NOS);

scientific theory;

learners' epistemologies;

models of intellectual development;

scaffolding of learning;

sociocultural reasoning

Introduction

This paper considers what secondary students studying in the English curriculum context understand about an important aspect of the nature and status of scientific knowledge. The discussion is informed by data collected from twelve 13-14 years old secondary students who were asked about their notions of what scientific theories are and about any theories they had met about the origin of the world and the origin of life on earth. In this paper we report how elicited student thinking compares to the type of understanding set out as target knowledge in secondary science; and consider how research into intellectual development indicates that careful scaffolding may be needed to bridge the 'learning demand' (Leach & Scott, 2002) between students' starting points and curriculum target knowledge. We explore the suggestion that teaching a modern (post-positivist) notion of scientific knowledge requires the development of specific strategies to 'scaffold' student learning.

The paper begins by reviewing how it has been increasingly recognised that science education should including teaching about the nature of science (NOS) as well teaching of specific science content. The challenge of reflecting modern ideas about NOS in the school curriculum is considered, and the particular curriculum context of the present study is explained.

The background to the study

The present study is informed by several areas of research and scholarship. In setting out a framework for the study we consider how teaching about NOS has increasingly been considered a major aspect of school science, and how this has been reflected in curriculum policy in the context of our study (England), although modern scholarship suggests that NOS is actually multifaceted and complex. We report a small scale interview study, and in discussing the results later in the paper we also consider ideas about intellectual development which can be used to understand the nature of student learning difficulties and the types of pedagogic approach needed to effectively teach aspects of NOS.

Teaching and learning about the nature of science

It is now widely accepted that science education at school level should include substantive specific teaching about NOS (Clough & Olson, 2008; Duschl, 2000; Hodson, 2009, 2014; Lederman &

Lederman, 2014; Matthews, 1994; McComas, 1998), rather than focusing exclusively on teaching current scientific knowledge. In part this reflects the 'science for all' notion that compulsory school science should not be designed around the needs of the minority of learners who will aspire to higher level study of science and science related careers. This has led to much discussion of the kind of science education which can be useful for all citizens (Millar & Osborne, 1998), something felt to be increasingly important in relation to both personal decision making (e.g. in following health related advice; in involvement in 'energy-saving' and recycling activities) and in terms of civic engagement (Sheardy, 2010) as voters, and possibly activists, asked to balance arguments about socioscientific issues such as environmental protection, and choices for future 'energy generation'.

It has long been common for school science courses to include practical activities that are considered to teach something of scientific method: how scientists come to scientific knowledge. The introduction of the 'heuristic' teaching method in the late nineteenth century (Jenkins, 1979) may be considered an early precursor of the sophisticated approaches to teaching science through enquiry advocated by some science educators today (Lawson, 2010). In the intervening century there was much scholarship suggesting that a key aspect of NOS - how scientists come to reliable knowledge of the world – was far from a simple matter.

The post-positivist turn in the philosophy of science

School science practicals ('experiments') can give the impression that hypotheses may be unproblematically tested to reach clear conclusions. As long ago as 1962, Schwab lamented how the presentation of scientific method in school texts books often implied a shift from hypothesis ('hopeful guess') to theory (supported by some tests, but not sufficiently to persuade all scientists) to 'fact' (or 'principle') through a verification process seen as "complete and unquestionable" (Schwab, 1962, p. 29). In reality science is usually far from this straightforward. Epistemology, the branch of philosophy concerned with how we come to knowledge, is subject to much professional debate, both among scientists and philosophers themselves (Brown, Fauvel, & Finnegan, 1981; Chalmers, 1982). Certainly, during the twentieth century, there was much scholarship which brought into question the idea of there being a simple 'scientific method' leading to definitive knowledge, although this has not fully impacted on school teaching practice (Williams, 2011).

One key influence was Popper's (1934/1959) seminal argument relating to the logical incompleteness of induction as a means to generate general statements about the world and the prescription that science required hypothetico-deductive methodology, which suggested that the development of new scientific knowledge always occurs within some assumed conceptual framework that is not itself tested in the context of a particular study. The logical operations involved in hypothesis-testing are always preceded by creative processes where the scientist imagines the hypothetical scenarios that could be tested (Taber, 2011b). Thomas Kuhn (1970) argued that because scientists worked within a 'disciplinary matrix' reflecting an established tradition (T. S. Kuhn, 1974/1977) - there was a degree of enculturation or socialisation involved in the conceptual starting points from which they interrogated research data to draw their conclusions. Following Kuhn, the postgraduate training of a research scientist can be seen as a kind of conceptual apprenticeship (Hennessy, 1993) where the apprentice scientist moves from peripheral to full participation (cf. Lave & Wenger, 1991) by being inducted into the paradigm that, in effect, defines the field for those working in that area of science.

Lakatos' (1970) model of science proceeding through Scientific Research Programmes offered a way to understand science as a rational process that could progress towards knowledge despite scientific enquiry necessarily relying on some metaphysical commitments that were not themselves tested empirically, and the necessary pragmatism of sometimes putting aside ('quarantining') unwelcome results and not treating them as falsifications - as a simplistic notion of scientific testing would require. This context of intellectual debate about NOS supported the development of a sociology of scientific knowledge (Bloor, 1991), and explicit questioning of the extent to which science could be said to have 'a', or indeed *any*, characteristic method (Feyerabend, 1988/1975). The Popper-Kuhn debate has been widely discussed (Kadvany, 2001; Mackenzie, Good, & Brown, 2014; Matthews, 2004), and an account of how the ideas of Popper, Kuhn and Lakatos can be framed as thesis, antithesis and synthesis - that is, Lakatos putting science on a rational footing that accommodates points raised by Kuhn's *description* of how science has proceeded which can be considered to undermine Popper's *prescription* for how science should proceed - is offered in Taber (2009). Osborne (2014) considers aspects of this debate in relation to teaching about NOS in school science.

Developing curriculum models of the nature of science

Given this complex range of scholarship, there is a problem for those charged with representing NOS in the school curriculum. It seems quite clear that the range and sophistication of the arguments made by various professional scholars who have explored scientific epistemology will not be directly accessible to most school age learners, if only because many of the discussants rely upon knowledge of particular philosophical positions and cases from the history of science to make their arguments, so school age students would lack the prerequisite knowledge assumed in such scholarship.

Curriculum designers need to set out a form of target knowledge for learners which manages to both be accessible for the intended age and level of students and yet is 'intellectually honest' (Bruner, 1960) in the sense of being an authentic simplification of the ideas presented in scholarship. Such a curricular model of the nature of science would need to represent scientific knowledge as generally robust and reliable, yet only taken as provisional (not absolute) knowledge of the world (Taber, 2008b). Kirch (2012, p. 851) has for example pointed out how curriculum standards in the United States expect upper elementary and middle school students to develop an "understanding that scientific knowledge is both durable and tentative and why this apparent contradiction is reasonable". Osborne (2014) suggests that there is wide consensus on what he refers to as a "basic set of features" of NOS which can inform appropriate curriculum, even if there is less agreement regarding how to best go about teaching NOS.

The curriculum context of the present study

The present study reports data from interviews undertaken with Y9 students (i.e. 13-14 year olds) attending state schools in England. A major revision of the English national curriculum programme for science, influenced strongly by arguments about the need to increase scientific literacy for all learners (Millar & Osborne, 1998), was introduced into secondary schools (QCA, 2007a, 2007b). This revised curriculum put much greater emphasis on what became known as 'how science works' (Taylor & Hunt, 2014; Toplis, 2011), such that teaching about the processes of science was given as much priority in the curriculum document as teaching about specific scientific topics. (The UK government have indicated that the curriculum will be further revised, but the formulation discussed here reflects the official curriculum context at the time of our fieldwork.)

Some extracts from the relevant curriculum document are presented in Table 1. For example, this document sets out 'scientific thinking' (p.208) as a key concept involving the use of models, theory generation, and critically evaluating evidence. The explanatory notes for teachers refer to the provisional and iterative nature of developing scientific knowledge and describe scientific theories as being "consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world" (p.208).

Extract from the curriculum programme of study section	Extract from explanatory notes
Scientific thinking a) Using scientific ideas and models to explain phenomena and developing them creatively to generate and test theories. b) Critically analysing and evaluating evidence from observations and experiments.	Explain phenomena: Science is not yet able to explain all phenomena but the process of developing scientific understanding constantly generates new and sometimes conflicting evidence. This in turn gives rise to new explanations and ideas. Theories: Scientific theories are consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world. They can, at least in principle, be tested by observations and/or experiments.
Applications and implications of science a) Exploring how the creative application of scientific ideas can bring about technological developments and consequent changes in the way people think and behave. b) Examining the ethical and moral implications of using and applying science.	Ethical and moral implications: Scientists, individuals and society need to think about the balance between the advantages and disadvantages of new developments before making decisions (e.g. examining issues relating to selective breeding and genetic engineering of plants and animals, to the production of potentially hazardous chemicals, and to the use of nuclear energy). The way scientific developments are achieved can also raise ethical and moral issues, for example experiments on animals to produce drugs that may prolong human life.

Table 1: Extracts from the English curriculum for teaching science to 11-14 years olds relating to Key concepts that underpin the study of science and how science works (QCA, 2007a; 2014)

This curriculum document reflects an engagement with arguments that secondary science should include learning about NOS and the societal impacts of science, such as the "ethical and moral implications of using and applying science" (see Table 1). Zeilder (2014) refers to issues that require students to evaluate moral and ethical factors as well as the technical aspects of science as socioscientific issues. Students were also expected to recognise that "modern science has its roots in many different societies and cultures, and draws on a variety of valid approaches to scientific practice" (p.208). The present study reports on interviews carried out during the 2008-2009 academic year, soon after the new curriculum was introduced.

The English curriculum also includes recommendations that lower secondary students (11-14 year olds) should be taught about aspects of the relationship between science and religion (QCA, 2004), and the present study derives from a broader project concerned with learning about this particular aspect of the interface between science and society - the 'Learning About Science And Religion' (LASAR) project.

The challenge of understanding the status of scientific theories about origins

The relationship between science and religion is a theme where there are diverse views - for example about the relative compatibility of scientific and religious accounts of the world (Barbour, 2000). It is common for secondary students in England, where most people do consider themselves religious (National Statistics, 2008), to see science and religion as being in opposition (Taber, Billingsley, Riga, & Newdick, 2011b), a view that has been strongly advocated by some scientists in the UK mass media. This reflects findings from other national contexts, where it has also been found that many students see aspects of science and religion as opposed (Francis, Fulljames, & Gibson, 1992; Fulljames, Gibson, & Francis, 1991; Hansson & Redfors, 2007; Long, 2011). Arguably, then, one aspect of NOS that should be explored in schools in contexts such as England is the wide range of positions on this issue taken by scientists (so, for example, allowing students to become aware that many scientists do not see being both religious and a scientist as necessarily incongruous).

Common perceptions that science and religion are necessarily in conflict have potential to cause difficulties for learners who see themselves as religious (Reiss, 2008). A particular issue is the potential for learners (especially from some cultural groups) to perceive scientific accounts of the origins of the universe and life on earth that are taught in school to directly contradict religious teaching - something that has been widely found in the US context (Long, 2011). We were then interested in how English secondary students made sense of scientific ideas about origins. The canonical knowledge here would be that

(a) scientists generally consider that current evidence most strongly suggests the Universe was formed in a 'big bang' event;

(b) scientists generally consider that there is a broad and extensive evidence base to support the notion that all life on earth has evolved from a common ancestor through processes of natural selection.

To scientists, the big bang and natural selection are both 'theories', which gives them the status of technically uncertain yet substantially supported and developed explanatory schemes - or in the language of the English curriculum "consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world" (QCA, 2007a). That is, scientists do not claim to be certain that these theories are correct, but do consider that they have the status of scientific knowledge. Scientific knowledge is seen as potentially open to revision, whilst often being well established through being grounded in carefully scrutinised evidence. This is of course a somewhat different notion to the traditional philosophical view that only 'reasoned, true belief' can count as knowledge (Matthews, 2002). A post-positivist view of science considers scientific knowledge can never have such absolute status, and is necessarily provisional (Taber, 2008b, 2009).

Student thinking about scientific knowledge

There is evidence from previous studies that students may not readily appreciate the nature of theoretical scientific knowledge (Hammer & Elby, 2000). Indeed, research suggests that school age students generally tend to have limited and often quite simplistic understanding of such aspects of NOS (Arnold & Millar, 1993; Hodson, 2009) and to operate with naive epistemologies (Carey, Evans, Honda, Jay, & Unger, 1989; Carey & Smith, 1993). Carey and Smith suggest three levels of understanding of the nature of science moving from (1) not distinguishing reality from ideas about reality; to (2) testing ideas that were in effect guesses about the nature of reality to see if they are (unproblematically) right or not; to (3) where the person "recognizes the cyclic, cumulative nature of science, and identifies the goal of science as the construction of ever deeper explanations of the natural world" (p.250).

Even at College level, studies report that science learners may have limited appreciation of the nature and status of scientific theories. Dagher, Brickhouse, Shipman and Letts reported four core conceptions of theory found among undergraduate students interviewed: that theory was "(1) equivalent to hypothesis, (2) an idea with evidence, (3) an explanation (ranging from tentative to established truth), to (4) an explanation based on evidence" (2004, p.742). Dagher and colleagues also reported that some students "made unsolicited contrasts between theories and laws, representing the latter as more certain than theories" (p.743) so that "determining whether a claim was theory or law was related to the amount and nature of supportive evidence" (p.746). Lederman and Lederman (2012, p. 337) suggest that this is a common pattern as "[i]ndividuals often hold a simplistic and hierarchical view of the relationship between theories and laws whereby theories become laws depending on the availability of supporting evidence".

A study to explore school children's perceptions of aspects of the nature of science that was carried out in the 1980s in Northern England collected data from nearly two hundred students (at ages 9, 12, 16) from a range of schools considered representative of the English system (Driver, Leach, Millar, & Scott, 1996). This research led to a three level model of student thinking in science, labeled as 'Phenomena-based reasoning', 'Relation-based reasoning' and 'Model-based reasoning'. Driver and her colleagues noted that "at the simplest level, scientific knowledge is portrayed as a picture of events in the world with little distinction being made between evidence and explanations" (p.111). Although these authors also found some evidence of students who considered "scientific knowledge as a theoretical model of events, a model which can be evaluated in the light of evidence" (p.111), their work suggested many school age learners were entering science classrooms with much less sophisticated understanding through which to interpret science teaching.

In particular, Driver and colleagues found that "the younger students tended to characterise empirical testing as a simple process of observation from which outcomes would be obvious" (p.84). When Driver and colleagues investigated what the school-age students understood by the term 'theory', they found that often their notions were quite vague, as well as being diverse: a vague idea, something known, a prediction, a kind of explanation. They also reported that "many younger students referred to a stereotyped image of scientists and made no distinction between their personal and professional concerns" (p.84). This is something which may be significant in the English context where the former professor of public understanding of science at Oxford University (Richard Dawkins) has made a series of popular televisions programmes presenting religion as an 'enemy' of reason and science.

A survey of 1702 Korean students at grades 6, 8 and 10 explored aspects of their views about the nature of science, including the tentativeness, and origin of scientific theory (Kang, Scharmann, & Noh, 2005). Kang and colleagues found that 15-23% (depending upon grade) of their sample responded with the view that a theory was "a plausible but not yet completely proven fact" (p.324) but that the majority of respondents selected an option that "scientific theories are facts which have been proven by many experiments" (p.325). Most of the respondents thought that scientific theories always (about 50%) or sometimes (about 40%) existed before being discovered by scientists rather than being invented by them (p.330).

Taber (2006) reported a small-scale study carried out about a decade later, where a modest sample (n=64) of lower secondary age pupils (11-14 year olds) from two English schools were asked about key science terms. Pupils were asked 'Have you come across the word 'theory' in science?' and (if they replied yes) 'Can you explain what a theory is?' The majority gave responses at the level of a theory being an idea, something that people think. A much smaller number gave responses suggesting that a theory had an uncertain aspect and should be considered 'unproven'. Other suggestions were that a theory was an explanation, an answer to a question, a prediction, a mathematical formula, or a hypothesis.

The same pupils were also asked 'Do you know any examples of scientific theories?'. The common responses were Newton's theory of gravity, Darwin's theory of evolution and Einstein's theory of relativity – and the only other acceptable suggestion was the big bang theory (although Pythagoras' theorem and Hooke's law were also suggested). Some of these secondary age students were unable to offer a single suggestion of a scientific theory.

Lederman and Lederman (2014) have recently reviewed research into teaching and learning of NOS, and noted that diverse studies into students' conceptions of NOS (undertaken at different times, and in various national contexts) have tended to identify similar problematic issues in student thinking. Among common themes identified where there is a learning demand (i.e. typical student conceptions are inconsistent with target knowledge in the curriculum) were the role of theory in scientific work; the distinctions between hypotheses, theories and laws; and how experimentation, models and theories relate to notions of absolute truth. Lederman and Lederman also reviewed research into the NOS related conceptions of teachers (and often teachers in preparation) and conclude that commonly teachers themselves have inadequate conceptions of NOS.

The present study

Since the research of Driver and colleagues (1996), and Taber (2006), there was the introduction of a new National Curriculum programme of study for science in England, which put great emphasis on learning about 'how science works'. The motivation for the LASAR project relates to concerns about the potential for perceived conflicts between science and religion to influence both science learning, and student attitude towards engaging in post-compulsory science study and science-based careers (Mahner & Bunge, 1996; Martin-Hansen, 2008; Reiss, 2008). Within the LASAR project we were interested in such issues as how students might consider science and religion to be related (if at all), and whether they appreciated why there might be different views on such issues. For example, we wanted to find out what the students knew of scientific and religious accounts of origins, and how they thought these different perspectives might be related .

Perhaps unsurprisingly we found students we interviewed adopted a range of stances on how science related to religion (Taber, Billingsley, Riga, & Newdick, 2011a). We explored students' 'epistemic insight' in terms of their appreciation of why people might come to different views about such matters as the origins of the universe and life on earth through semi-structured interviews (Billingsley, Taber, Riga, & Newdick, 2013). Analysis of interviews undertaken with twelve 13-14 year olds students suggested that five of them showed a limited level of epistemic insight, and seven offered no evidence of appreciating why there should be a diversity of views.

The present study considers how these students understood the status of scientific theories of origins. As well as asking students what scientific ideas about origins they were aware of, we wanted to find out how students understood the nature of these ideas as scientific knowledge.

The research question we investigate in the present study is:

How do 13-14 year old students in England perceive the nature and status of scientific theories about origins?

We chose to focus on students in Year 9 (Y9, 13-14 year olds) because they were in the final year of the lower secondary phase (known as Key Stage 3 in England) during which it was recommended that students should learn about the relationship between science and religion (QCA, 2004).

Methodology

In the phase of the research reported here, we worked in four schools. In each of these schools we interviewed three students from one Y9 class. Our interviews were semi-structured, adopting a general approach which has been used widely in science education to elicit students' thinking about various topics in relation to conceptual understanding, attitudes etc (Bell, 1995; Gilbert, Watts, & Osborne, 1985; White & Gunstone, 1992). In the interviews, informants were asked about the extent to which they had previously considered the issue of science and religion; their ideas about key terms used to describe ideas in science (see the Appendix); sacred texts; prayer; miracles; and about the range of views people have about the origins of the universe and of life on earth.

All pupils gave informed consent for the interview, and for it to be recorded so the data could be used in our research. The students were made aware they were under no obligation to answer particular questions or complete the interview; and that any data would be used anonymously. All interviews were carried out in sufficiently private locations in the pupils' schools by one of the research team (FR), and were recorded using a digital voice recorder.

Elsewhere we have reported on the stances that our twelve interviewees took regarding to the relationship between science and religion (Taber et al., 2011a), and the extent of their 'epistemic insight' into the diversity of stances that people take on this issue (Billingsley et al., 2013). The present paper however is focused on the way these young people understood the nature and status of the scientific theories they were asked about during the interviews.

The sample

The sample for the present study comprised students from one Y9 class in each of four diverse English secondary schools (see Table 2), including one Church school, giving some reassurance that findings reflect the diversity of schools in England. (Something like a third of state funded schools in England have an association with a religious faith or denomination: most commonly the Church of England or the Roman Catholic Church. The church school participating in our study had an association with both of these denominations.) We assigned our host schools and student interviewees assumed names during analysis, and these are used in this report.

School	Locale	Region of England	Size (Pupils)	Notes	Study participants
Abbey Church School	small city centre	East	c.600	Church school	Andrea Anita Alisha
Borough Comprehensive	suburb of large city	South East	c.1600	No selection of pupils in terms of religion, ability or gender.	Ben Barinda Brenda
Ceeside Comprehensive	coastal town	North East	c.400	Area of relative social deprivation	Chas Christine Colin
Dalesview Grammar	small rural town	North	c.600	School selects on ability – admits boys only	Dominic Dean David

Table 2: Some characteristics of the study schools

The main criteria for identifying interviewees were that their teacher judged they would be comfortable talking to us, and forthcoming in an interview context. We did not set out any criteria in terms of ability or school achievement, but we did seek an approximate gender balance across the sample taken as a whole.

Analysis

All interviews were transcribed from the digital recordings (by FR). Initial analysis was carried out by the first author. In view of the 'qualitative' nature of the data collected, a multi-stage interpretative approach to analysis was undertaken without imposing pre-developed categories onto the data (Strauss & Corbin, 1998). Moreover, in keeping with the idiographic nature of the study, and our view that investigating perceptions of complex topic areas requires an in-depth approach respecting the complexity of individual thinking (Taber, 2008a), the data from each informant was initially considered separately, before looking for patterns across the twelve cases.

Findings

Although, as would be expected, there was some variation in what the students told us about the origins and status of scientific knowledge (which we explore further below), a common general pattern seemed to be that (a) scientific theories were considered imaginative ideas that scientists had, which were then subject to testing which (b) usually unproblematically established whether they were true: in which case they might then be considered to take on a new status as laws of nature.

The two main features of this pattern then were (i) that theories are human constructions and apparently often little more than guesses at explanations; and (ii) science can generally produce definitive knowledge through testing as that provides proof of the truth (or otherwise) of scientists' ideas. Examples of student comments relating to these two features are reported in Table 3, which presents comments elicited from each of our interviewees.

The status of theories

Compared with the statement in the lower secondary science curriculum that theories were "consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world" (QCA, 2007a), most of the descriptions offered by our interviewees suggested a very different status: a scientific guess; an opinion; a hypothesis; an idea; a belief; a made-up placeholder for an explanation; a myth (see Table 3). In a number of these cases, the possibility of testing the theory was explicitly mentioned: i.e., that it had not yet been proved/is not proved; can be proved right or wrong; should be proved (see Table 3).

Interestingly, the three students who suggested a theory might already have some evidence - a belief supported by evidence; an idea that's got some proof, but not fully proven yet; there's some evidence to support it, but it hasn't been outright proved yet – were all members of the same class.

Student	The origins of theories	The status of scientific knowledge
Andrea	"a theory is … a guess, but it's a very scientific guess"	"once you've got a theory, you have to work on it until it can be proved" "they did a number of experiments and it was proved that ['big bang' theory] was the only way the universe could've started"
Anita	"[a theory is] someone's opinion…it's like a hypothesis or something"	[law of nature] is "what happens like, it's just a regulation, and is definitely what happens"
Alisha	'[a theory is] just a method that hasn't yet been proved, it's just like an idea someone has…it can't really be like a fact or anything [as] it hasn't been proved"	"Isaac Newton's laws … probably did originate as a theory, but I think he obviously was able to test them"
Ben	"[a theory is] something that explained some things… it's what you believe is true or false"	"people that have researched it, so, they know what is true – they can make it law"
Barinda	"an idea of how it happened, and then it's something that should be proved… it's an idea… it's mostly an idea"	"it's something that should be proved, and then it'll become a fact…you have to prove it to make it true"
Brenda	"[a theory is] scientists – it's their idea of what happened, what they come up with…some of them I think are just made up, because they can't find any other explanation, so they kind of think of [an] other thing to try and explain it…until they find out more"	"most theories are true" "[laws of nature are] what has to happen for nature to happen, in a way"
Chas	"something that isn't proven, that people believe in, that's what I think a theory is"	"[the law of gravity is] proven fact, gravity does exist, because they proved it"
Christine	"[a theory is] sort of like a myth…like a story, that you don't know the answer to, it's just what you think what would happen"	"[theories are made true by] facts [established by] "people working together, and finding out an answer" "[laws of nature derive from] experiments, I think a load of people experiment a load of things"
Colin	"[a theory is] an opinion of someone, that can be proven right or wrong [by] proof, definitely proof"	"the scientific version of a law is something that is most certainly true, can be proven, and has been noted as true"
Dominic	"[a theory was] when a scientist has an idea, that could prove, or explain why something happened, or how it's come to happen, but …there's some evidence to support it, but it hasn't been outright proved yet"	"a theory, but it's been proven…can become fact" "[laws are] something that's been proven, that just happens, and can't be disobeyed, in a way, like a rule…I think someone's found it out that that happens, and then they've gone on to find a lot of evidence for it"
Dean	"a theory is a belief supported by evidence…the thing about scientific theories is, a lot of them can't be proved"	"some things can be ultimately proved, but a lot of things can't be"
David	"[a theory is] an idea that's got some proof, but not fully proven yet – so it's before it's become fact…it's like an idea that's could be right, but it's not been fully proven yet"	"the laws of physics… what has to happen… they become laws of physics, after it's been proved"

Table 3: Student comments about the nature and status of scientific theories and laws

'Proving' theories

For most of our interviewees, experimental testing resulted in a transition from ideas which were little more than imaginative musing to proven 'facts', with little room for anything intermediate. So for example, when we asked Alisha about some well-developed scientific theories, she recognised that theories were not understood as definitive, absolute knowledge, but instead saw them as merely conjectural,

> Interviewer, I: The next two questions refer to … the big bang theory and the theory of evolution: what do you think a theory is?
>
> Alisha, A: Just a theory.
>
> I: Mm?
>
> A: Well I think it's like – it's just a method that hasn't yet been proved, it's just like an idea someone has, but I'm not sure that a theory – um, it can't really be like a fact or anything – it hasn't been proved, so.

In general, our study participants offered very limited explanations of how the testing process was able to produce definite knowledge, even though they seemed confident enough that such a process occurred. Generally – as we discuss below - their explanations could be considered to encompass naïve empiricist and/or rationalist views, i.e. that the evidence of experience and/or thinking about the phenomena showed simply and clearly what was the case. Although student comments generally implied this was very straightforward, one of our informants saw the process as being more drawn out, and as a community effort. Another seemed to go beyond this, suggesting that it was the decision of the scientific community that determined truth status (see below). There were also some acknowledgements that some scientific ideas might not be open to being readily proved or disproved (again, discussed below). However, only one of our interviewees offered a clear indication that scientific ideas provisionally considered proven should still be considered as open to later challenge.

Naïve empiricist/rationalist views of science

Andrea described how proving a theory involved finding 'reality':

> once you've got a theory, you have to work on it until it can be proved, so there'll be people working on the big bang, and it can't just be a random guess, there has to be some traces of fact – reality - in it. You just need to find all of the reality, and kind of make sure

> that you've got a good percentage of truth in the theory, instead of just it all being completely made up

Andrea suggested that in the case of the 'big bang' theory, "they did a number of experiments and it was proved that it was the only way the universe could've started". Of course, scientists working on this scientific problem would not claim that they have definitively proved the big bang occurred.

Anita thought laws offered definitive knowledge, "definitely what happens", and that such laws derived from direct observation of nature: "from people observing them and like comparing them to like what other things do within nature, and then – yeah – write down a list of laws of what happens". She seemed to feel this (naive version of Baconian induction) was an unproblematic process "because you can like watch the laws of nature and you can like hopefully trust your eyes".

Some of our informants went as far as to suggest that it could become obvious whether a theory was true or not. Anita, for example, thought that theories could be judged to have different status: true; obviously wrong; and ridiculous or weird. She had heard that "some theories say that we could just be dreaming and we wake up and it's completely different, so it's kind of weird", whilst "some are true…'cos some are just completely ridiculous, and others do actually have evidence supporting it". An example of a theory that was not true was "the flat Earth, that is completely ridiculous, because we already know that it's round". The sense of obviousness here also referred to the "phlogiston theory, because as soon as Lavoisier like proved it wrong, it was obvious that it was". Scholarship into the history of science offers a very different view - the celebrated chemist Priestley, for example, certainly did not find this conclusion obvious (Thagard, 1992). However, Anita seemed to feel that deciding whether a theory was true or false was ultimately straightforward.

Dominic thought theories could be proven true, and talked about the example "in like astronomy the idea of us going round the Sun was thought a theory, but it's been proven – obviously – so they can become fact". Similarly, he thought for a law: "I think someone's found it out that that happens, and then they've gone on to find a lot of evidence for it, and over time people have sort of come to realise that that is just what happens". Colin also seemed to feel there was a straightforward relationship between ideas and evidence so that theories could be shown to be true by "proof, definitely proof", and offered the example of "the theory of evolution" where "you get fossils, and then new fossils of the same sort of thing".

The role of the scientific community

Christine's comments also suggested that the truth of scientific ideas could be determined by a straightforward process, albeit she recognised this could be hard work. She offered a view of how the scientific community came to agree on whether scientific theories are judged as true scientific knowledge:

> they must use their brain a lot, and just try and work out, but then there might be another scientist who works out those facts – they say their theory, then someone with their own mind thinks their theory, and then I think they put it together … to get one big theory

Theories were made true by "facts!", which could be established by:

> people working together, and finding out an answer … they'll put all their heads together on a computer and typing really quick[ly] and looking, finding something … I reckon they'd go on the computer and find a subject, what is relevant to the main subject.

An alternative source of information "could be books" such as the "text books we have at school – that has a load of information in". Such sources of information were reliable because if they reported some event, "it must have been an event what happened, and [the scientist] had to jot it down, write it down in some shape or form". Christine thought this was how scientists worked, that "if an event happens, then I'm sure they'd write it down…keep it in a file or something". For Christine, deciding between rival theories seemed to be a simple empirical matter, as for example "a theory…that the Big Bang could explode the Earth [presumably a reference to the Large Hadron Collider which had been a focus of much media attention] … And then, when it happened, you was 'oh no, it's not true', but some scientists thought it was".

Scientific knowledge established by agreement

Ben offered a slightly different perspective than most of our informants in that he seemed to support, if not a relativist view of knowledge, then perhaps a conventionalist one where truth was established by agreement. He thought that a scientific theory was "something that explained some things" and was open to being "debated about". He considered that theories were not true in an absolute sense: "not all of the time – it's not really a true or false, it's what you believe is true or false, so some are true, and some can be – that some people believe that some aren't". He implied that theories could be considered true, if they were "something that everyone can agree to", "like obvious things – stories that are quite obvious, that everyone can agree to" rather than "something that challenges something else".

Despite this, Ben also thought that a theory had to have some basis, otherwise "you have no evidence that it is true, because if you just make a theory up for no reason, you can't really prove that it's right or wrong". This second meaning of a theory being proved true seemed closer to his notion of a law as something that tells us "the way things go". Such laws were established by scientists when "people that have researched it, so, they know what is true – they can make it law".

Limits of science

Some of our informants recognised that finding proof for historical events (origins) could be problematic. Alisha suggested (contrary to Andrea's view reported above) that in the case of:

> the big bang, there's not enough equipment to be able to see if it's true or not, although I think they tried … I don't think it *can* be proved as such, because it's already happened, and I don't think there's any way of answering that.

Dean thought that "some theories are [true], and some theories aren't, but the thing about scientific theories is, a lot of them can't be proved". As an example he gave "evolution …you can't prove it, but there's very strong evidence, and people tend to believe in it a lot now". He thought there was "a very big difference" between evidence and proof, as "evidence is something that gives you ideas about it, something that supports your theory, but proof is something that says this is definitely true, this is exactly what happened". As he explained his thinking, Dean seemed to doubt that there could ever be absolute proof,

> you can't really find proof for a lot of things, some things can be ultimately proved, but a lot of things can't be, but you can get very strong evidence … I don't know – I don't think … there <u>is</u> such thing as proof … I think there's strong evidence, like … there's camera footage of you doing it or – something, but there's still not really proof

So Dean considered that scientific knowledge had limits as,

> we're doing astronomy at the moment – as an optional lunch-time sort of lesson-thing, and … it suggests a lot of things that *don't* follow the laws of nature, things that shouldn't really happen and nobody knows why … like Dark Matter and Black Holes, things that nobody *really* knows what they are

Scientific knowledge as fallible

David also seemed to have a somewhat less absolute sense of 'proof' than some of our other informants. He referred to how ideas "become laws of physics, after it's been proved", and how for a theory to be considered true "you'd need some proof, and it needs to be logical, I'd have thought". He suggested that in the example of "evolution – it makes sense that people have evolved over time … I think there's proof for it, yeah, like fossils, from a long time ago". However, such 'proof' could not be considered absolute: "I don't think for all time – no, but I think for now they do make sense and that's what seems like the obvious answer". This particular response seems somewhat closer to the spirit of the curriculum description of a theory as a "consistent, comprehensive, coherent and extensively evidenced explanation" (QCA, 2007a).

Discussion

The English National Curriculum document for teaching 11-14 years old represented scientific theories as "consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world" (QCA, 2007a). That was not how most of our 13-14 year old interviewees tended to understand the term: for most of them a theory was little more than an idea dreamed up, that was yet to be proved or dismissed. This would not matter greatly if this was simply another example of every-day associations of technical terminology (Watts & Gilbert, 1983): after all, in everyday discourse, 'I have a theory about that' usually refers to an idea, guess or hunch, just as our study participants tended to use the term. However, the notion of a 'theory' does important work in understanding the NOS, and what is problematic is not the misunderstanding of a term, but transferring the association to scientific knowledge. So, in science, Darwin's theory of natural selection; Lavoisier's oxygen theory of combustion; and Einstein's theory of general relativity, may not be absolutely proved facts, but are considered as a good deal more than just good ideas or lucky guesses.

If the findings from the modest sample of students interviewed for the present study reflect the wider English context then this would suggests that despite the curriculum revisions intended to increase emphasis on 'how science works', students near the end of the lower secondary phase (13-14 year olds) generally retain simplistic notions of the nature of scientific knowledge. So where the curriculum document posits how "scientific ideas and models" are "used to explain phenomena and develop... them creatively to generate and test theories", most students would seem to see theories as ideas not yet tested, but with potential to become something other than theories if proved. Often that 'something else' seems to be 'laws', which is unfortunate as laws (usually understood as regulations in nature) are descriptions of observed patterns, and not explanatory schemes. Theories can be reconsidered because "developing scientific understanding constantly generates new and sometimes conflicting evidence" (QCA, 2007a, p. 208).

Core NOS concepts such as theory, model, law etc. do not have entirely agreed definitions, even among scientists and philosophers (Hodson, 2009), and are complex notions that necessarily need simplification before they can be understood by school age learners (Taber, 2008b). When we mentioned the theory of evolution to Anita and asked her what a theory was, her characterisation that a theory was "like someone's opinion...like a hypothesis" demonstrated not only a limited appreciation of the nature of theories, but consequently a failure to appreciate the status scientists give to evolution when referring to it as a theory. As evolution has often been a core issue in debates about religion and the teaching of science in schools (Antolin & Herbers, 2001; Prinou, Halkia, & Skordoulis, 2005), this is more than a technical shortcoming. If the theory of evolution was just an opinion or a guess, then choosing between evolution and anti-evolutionary accounts of human origins would be little more than a matter of personal taste.

Among our small sample of interviewees, there was some awareness of the necessary limits of 'proof' in science, and of the role of the scientific community in deciding what counted as scientific knowledge. However, in general, theories were not distinguished from hypotheses or simply ideas; and converting such hunches into definitive scientific knowledge was often presented as an unproblematic matter of testing and proof, where observation could offer direct and 'obvious' evidence. This reflects findings from previous studies (Driver et al., 1996; Hammer & Elby, 2000) and aligns much of our participants' thinking with "what is prescientific, the reality which seems self-evident to [people] remaining within the natural attitude" (Schutz & Luckmann, 1973, p.3).

The students participating in this study seemed to largely be operating with a dichotomous notion of scientific knowledge (as represented in figure 1) as either (i) not-yet-tested and so little more than a fancy or guess (e.g. 'theory') or (ii) proven by being tested against the evidence (e.g. a law): in keeping with the pattern that Lederman and Lederman (2012) suggest is common. A US longitudinal study exploring epistemological development reported that "between [ages] 10 and 16 … issues of 'fact' and 'opinion' became less sharply differentiated" (Mansfield & Clinchy, 2002), and some of our 13-14 year old interviewees seemed to be ready to move beyond the sharp distinction between theories (as ideas) and laws (as proven). Our interviews certainly provide suggestions that some of our participants were starting to appreciate that definitive testing may not always be possible, and that some theoretical ideas may be considered well supported by evidence. However, there was limited evidence that these students saw scientific knowledge as existing on a continuum that allowed continuous variation (and change) in the extent to which ideas might be considered as reliable scientific knowledge – as, over time, different evidence is collected, critiqued, checked, compared etc. Rather, these secondary students tended to think scientists carried out experiments that prove a theory to be correct (e.g. the big bang for Andrea) or obviously wrong (e.g. phlogiston for Anita).

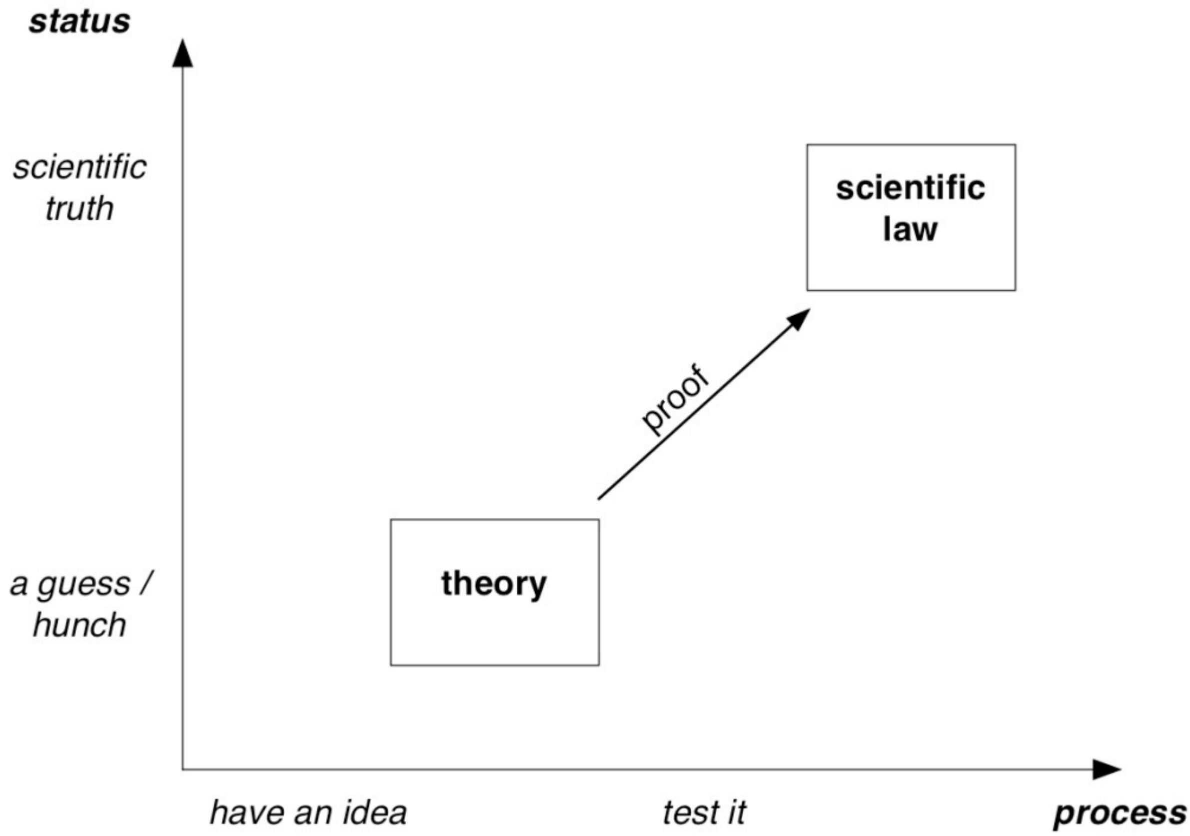

Figure 1: Student understandings of scientific epistemology were generally simplistic. For most interviewees theories were just ideas, until they were proved to be correct

The general impression was that theories were largely seen as yet-to-be-supported products of imagination, and that testing them was largely straightforward. This seems especially significant given that the foci we suggested to elicit evidence of students' thinking concerned especially challenging topics for scientists (the origins of the universe, and of life on earth).

Why does the nature of scientific theory present such a large 'learning demand'?

The target knowledge about the nature of scientific theories set out in the English curriculum seems to present a substantial learning demand (Leach & Scott, 2002) as the thinking elicited from students often appears to be considerably different from the level of sophistication set out as target knowledge. These findings are broadly consistent with earlier studies that suggested that English school students' notions of scientific epistemology were often vague and simplistic (Driver et al., 1996), despite repeated attempts to strengthen such aspects of the NOS in the school curriculum (Johnson, 2004; QCA, 2002, 2005, 2007a, 2007b).

In part this could reflect limitations in teaching. The present study explored aspects of student thinking in a context where there are formal expectations about teaching the NOS, but did not investigate the teaching that students actually experienced. As Williams (2011, p. 39) has noted "if teachers are themselves confusing the scientific meaning of, for example, the word 'theory' with a more vernacular meaning, then there is even less chance that pupils will acquire [a canonical] understanding". We note that the simple model represented in figure 1 could be considered to reflect the approach to teaching about scientific enquiry through 'investigations' (so-called 'fair testing' of simple hypotheses through controlled experiments) that was the model of scientific method legitimised in the English science curriculum for almost twenty years (DfEE/QCA, 1999; Taber, 2008b).

However, it is also useful to consider models developed from research into intellectual development, as these suggest that there may be a significant gap between the current aspirations of curriculum models and the forms of thinking typical of secondary school learners indicating that particular pedagogic strategies may need to be developed for effective teaching of NOS topics.

Intellectual development as a potential constraint on understanding NOS

Research into cognitive development suggests that school age learners may not readily engage in the more sophisticated forms of thinking needed to appreciate key features of NOS commonly considered an important part of the school science curriculum. The notion that human cognitive development tends to continue through childhood and adolescence was a core commitment of Jean Piaget's research programme, which impacted widely on educational thought. Piaget's (1929/1973, 1970/1972) highly influential stage theory of cognitive development - which was once mooted as "an epistemology for science educators" (Kitchener, 1993, p. 145) - suggested that "the matching of science concept to pupil's intellectual level is very important to ensure pupils' understanding of science" (Bliss, 1995). According to Piaget's model, the typical child only starts to develop the 'formal operations' that allow them to operate hypothetically, and carry out meta-operations (i.e. to carry out mental operations on purely conceptual entities), something fundamental to most scientific workat the beginning of the secondary years (11-12 year olds).

Piaget's work has been criticised on a number of grounds (Sutherland, 1992) and in particular from socio-cultural and cultural-historical perspectives (Bruner, 1960; Leach & Scott, 2008; Smardon, 2009) drawing for example on Vygotsky's (1978) ideas about how teachers and others can 'scaffold' (Wood, 1988) learning (discussed further below). In reviewing research that considers brain development, Kuhn (2006) has suggested that limitations in children's and adolescents' unsupported performances on some tasks may be explained by the development of the frontal lobes which support executive control (decision making, monitoring engagement etc) continuing through adolescence. Other theorists suggest that apparent 'deficiencies' in cognition often relate to lack of familiarity with specific domain knowledge, rather than inadequate core processing capacity (Demetriou & Mouyi, 2011).

Piaget's focus was on logical operations of the type that, for example, supports understanding how to set-up, or draw conclusions from, a controlled experiment (see Table 4). Yet in science clear crucial experiments are rarely available (Lakatos, 1971/1978), and knowledge is always open to re-examination, and may be supported by available evidence to varying extent. Zeidler (2014) has pointed out that in general a more robust understanding of the nature of science is associated with higher levels of epistemological sophistication. To understand NOS, students need 'post-formal' thinking (Arlin, 1975; Commons, Richards, & Armon, 1984; Kramer, 1983) that allows them to appreciate that scientific theoretical knowledge exists on, and shifts along, a dimension representing the degree of support provided by the (currently understood) interpretation of available evidence. Sadler, Klosterman and Topcu (2011, p. 48) refer to a construct they label 'socio-scientific reasoning' that involves:

- recognising the inherent complexity and multifaceted nature of socio-scientific issues;
- analysing issues from multiple perspectives;

- appreciating the need for ongoing inquiry related to such issues (n.b., current knowledge is not final);
- employing skepticism in the review of information presented by parties with vested interests.

This requires the ability to adopt multiple perspectives (Roberts & Bybee, 2014), and would seem to require what Sternberg (2009, p. 363) calls wisdom: "post-formal-operational thinking" that "requires balancing of multiple and often competing interests".

Learning context	Fair testing model of scientific enquiry	Post-positivist notions of scientific knowledge	Socio-scientific issues
Demand on learners	Application of logic to decide if experimental results match deductions of hypothesis	Ability to compare and evaluate alternative theoretical perspectives used to interpret complex and indeterminate evidence base	Drawing upon scientific knowledge as one type of evidence when comparing and evaluating arguments drawing upon different interest and value positions

Table 4: The demands of learning about scientific knowledge

However research suggests this kind of thinking is not always adopted by learners even at university level. Based on work with elite undergraduates Perry (1970, p. 3) produced a scheme of 'intellectual and ethical' development, moving from "simplistic forms" in which a person understands issues "in unqualified polar term of absolute right-wrong, good-bad" to "complex forms" where a person forms "commitments in a world of contingent knowledge and relative values". Perry's findings have been reflected in many other studies (Ashton-Jones & Thomas, 1990; Eastwood, Schlegel, & Cook, 2011; Hofer & Pintrich, 1997; Kohlberg & Hersh, 1977; D. Kuhn, 1999).

Deanna Kuhn (1999) has argued that critical thinking, widely considered a major aim for schooling, should be understood in a developmental framework, and she proposed four stages:

- Realist: where reality is directly knowable, and certain knowledge is acquired from an external source, and where assertions are copies of external reality;

- Absolutist: where reality remains directly knowable, and certain knowledge is still acquired from an external source, but where assertions may be correct or incorrect, so people can have false beliefs;

- Multiplist: where knowledge is generated by human minds (and so is uncertain), and individuals freely form their own opinions of the way things are;

- Evaluative: where knowledge is generated by human minds (and so is uncertain), but where different assertions may be evaluated and compared by argument from evidence, using established criteria.

Learning about such NOS features as the nature of scientific knowledge, and demonstrating socioscientific reasoning, would require students to work at the 'evaluative' stage (see Table 4) whereas Perry's work would suggest that even many tertiary students tend to operate at the relativist 'multiplist' stage, where the loss of absolute knowledge is understood as justifying intellectual anarchy (i.e. if we cannot know for sure then all opinions are admissible, and there is no objective way to choose between them). Palmer and Marra (2004), undertook a grounded theory study of college students in the US and concluded that the shift from the early absolutist stage to the middle relativist stages occurred later in the context of natural science contexts, than in the humanities and social sciences. Whilst such a result could say something about the typical mind sets of students attracted to different disciplines, this could also reflect the greater opportunities for engaging with live debates in humanities subjects, whereas science has commonly been presented as a 'rhetoric of conclusions' . This, invites consideration of how learning experiences can promote the development and recruitment of more more sophisticated approaches to thinking.

Implications for teaching and research: From "an idea someone has" to "consistent, comprehensive, coherent and extensively evidenced explanations of aspects of the natural world".

Research into intellectual development suggests then that secondary age learners are likely to face a large learning demand (Leach & Scott, 2002) when asked to engage with aspects of NOS (such as the status of scientific knowledge), or socioscientific issues (such as understanding why people will take such diverse views on the compatibility of science and religion). . Research suggests that teachers can not assume that the kinds of thinking students need to apply to be successful in these key areas of the science curriculum are readily engaged by most school age students. This need not imply that these curricular goals should be abandoned, but may indicate that teaching needs to be infused with instructional approaches developed to help learners bridge the learning demand.

Piaget's theory was commonly used to suggest what should *not* be taught to certain age groups because students would not have achieved the required level of development. This interpretation is generally considered to be discredited (Silcock, 2013) and actually a key feature of Piaget's theory was that cognitive development occurs through interaction between the learner and their environment, and in particular the social environment which acts to modify thought (Piaget, 1950/2001). Therefore age-related surveys reflect what is typical in a population (Shayer & Adey, 1981) rather than necessary limits on what students could achieve - given suitable environmental support. Piaget's own position was much closer to the bidirectional relationship suggested by Demetriou, Spanoudis & Mouyi (2011, p. 629) when reviewing current thinking about cognitive development and education: that is "Cognition shapes and affects learning in schools, and schooling shapes and affects cognition".

This has been demonstrated with the programme known as 'Philosophy for Children', designed to be taught across the years of primary and secondary schooling, and which uses carefully designed novels to model features of thinking as a starting point for developing communities of enquiry that engage in genuine dialogue (Lipman, 1998). This programme has been widely adopted, and much studied, and has been consistently found to effect the development of aspects of critical and creative thinking (Trickey & Topping 2004).

The notion of scaffolding may be highly relevant to effective teaching of NOS. Vygotsky (1978) proposed the concept of a learner's zone of next (or proximal) development as a key area in a kind of hypothetical achievement phase-space. This is the zone where a learner cannot yet achieve unaided, but may succeed with some vicarious support - and therefore this is also the zone where development can readily be supported. Scaffolding (Wood, 1988) is the strategy of providing selective support in the zone of next development that is incrementally withdrawn (faded) as the learner learns how to achieve unaided - so the zone of *actual* development grows, and the zone of *next* development shifts into what had been a zone beyond even supported achievement (Taber, 2011a).

This approach has been used to support early secondary learners in moving towards mastery of scientific ideas requiring formal operational thought (Adey, 1999) - with reported outcomes that are long-lasting and domain independent (Adey & Shayer, 1994, 2002) - and something similar is needed in terms of helping learners develop the kind of epistemic insight required to appreciate aspects of NOS and how science interacts with other aspects of culture. Levinson (2011), for example, highlighting the complexity of studying 'controversial' socio-scientific issues in the secondary school classroom, suggests an approach to breaking down the learning demand, and gradually inducting students into consideration of more "open and messy" (p.69) issues. Zeidler (2014, p. 712) reports that by giving careful attention to sequencing of instruction about socioscientific issues, and adopting pedagogic approaches that will lead to students experiencing 'cognitive and moral dissonance', it is possible to facilitate progression in students' use of reflective judgement.

Teaching is about finding ways to make the unfamiliar familiar, and there are strong arguments for the use of historical case studies in teaching about NOS (Allchin, 2013; Matthews, 1994). However, other pedagogic techniques may also be useful, especially with younger learners who may lack the science content knowledge to fully appreciate such cases. For example, it may be possible to draw parallels between features of NOS and context more familiar to students from their everyday lives. Perhaps familiarity with detective stories - with their multiple suspects, gradual uncovering of evidence, and occasional misleading 'red herring' clues might offer one candidate (perhaps even drawing upon the fictional modelling approach used in Philosophy for Children, referred to above). Possibly discussing a question such as 'which is the best' pop group or sports team might offer a chance to appreciate why some questions do not have definitive answers that lead to ready consensus. Objective measures (the team top of the league, or that has scored the most goals) may be mixed with value judgements (the colour of the kit, a preferred style of play) and more contingent factors (the local team, the team parents support). There are challenges as well as affordances in teaching through these kind of analogical models (Gentner, 1983) and these suggestions are simply meant to offer examples of the kinds of techniques that might be explored to scaffold learning to bridge a substantial learning demand.

The present study reflects much previous research in suggesting that important recommendations for a greater emphasis on teaching NOS and socioscientific issues at school level assume access to more sophisticated thinking than is commonly exhibited by most school age students when asked to engage with these aspects of the science curriculum, suggesting that development and evaluation of specific pedagogic approaches is indicated. Effective instruction in this curricular area could support educational aims beyond science learning, as Demetriou, Spanoudis and Mouyi (2011, p. 635) argue that in order to support intellectual development, education at secondary level should provide opportunities to "build epistemological awareness about the characteristics, possibilities, and limitations of different knowledge domains vis-à-vis their methods, functions, and priorities". Teaching about the nature of (scientific, and other disciplinary) knowledge therefore potentially has an important role in providing learning opportunities that can actually support intellectual development. Meeting these educational aims for most learners of school age may depend upon developing scaffolding strategies to help learners bridge a significant learning demand. A research programme to develop and evaluate potential learning scaffolds would seem to be indicated.

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Appendix: The interview protocol

The semi-structured interview had a number of sections (see Taber et al., 2011a). The guide questions for the section of interview that forms the basis of the present study were:

- What do you think a theory is?
- Are theories true/have they been proved?
- Have you learnt about any laws of nature? (which one(s)?)
- What do you think a law of nature is?
- Where do you think laws of nature come from?

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