UNIVERSITY OF CAMBRIDGE
Faculty of Education

ISSN 2043-8338

Journal of Trainee Teacher Education Research

The scientific personal epistemology of students aged 11-12: A case study

Jamie Linale

(PGCE Biology, 2018-2019)

email: jl2054@alumni.cam.ac.uk

Abstract

The intention of the study was to explore the scientific personal epistemologies (SPEs) of students aged 11-12. A student's SPE is how they conceive the nature of knowledge and knowing in science. Personal epistemology, Nature of Science (NOS) and Scientific Inquiry (SI) research informed methodology and analysis. The case-study employed a battery of instruments, including concept cartoons, closed-form and open-form questionnaires, and inductive and deductive coding of responses. Consistent with previous findings, students entering secondary school have a nebulous and unstable conception of the discipline of science, and a rudimentary and inconsistent SPE. Developing more sophisticated SPEs is essential in science education, and educators should be sensitive to students' likely rudimentary conceptions at and before age 12. As students have the potential to hold more sophisticated epistemologies after appropriate intervention, both primary and secondary science educators should encourage explicit engagement with personal epistemology, NOS and SI in the classroom.

https://doi.org/10.17863/CAM.84142

The scientific personal epistemology of students aged 11-12: A case study

James Linale

Introduction

The United Kingdom national curriculum states that one of the aims of science education is to "ensure that all pupils … develop understanding of the nature, processes and methods of science" and "are equipped with the scientific knowledge required to understand the uses and implications of science". Science education is, fundamentally, about training students to 'be' scientists; this should equip students with the knowledge, practices and values to pursue careers in science, to be scientifically-literate citizens (e.g. Lederman, 1986), and to effectively exercise similar skills in the social and political domain (e.g. Popper, 1945/2012). It is important to establish students' understanding of scientific personal epistemology (SPE) – their views on the nature of knowledge and its production in science – in order to, *inter alia*, facilitate conceptual change where necessary and to evaluate the efficacy of pedagogical theory and classroom practice. The aim of the present study was to explore the SPE of students aged 11-12.

Personal epistemology

Personal epistemology: its basic form

Personal epistemology, is one's own (i.e. personal) theory of both knowledge and knowing, the "nature of knowledge and its production" (Sandoval, 2005, p.636) - encompassing, *inter alia*, the structure and nature of knowledge, its sources, and the justifications one uses in accepting, constructing and holding knowledge claims. According to Hofer and Pintrich (1997), personal epistemology is "how individuals come to know, the theories and beliefs they hold about knowing, and the manner in which such epistemological premises are a part of and an influence on the cognitive processes of thinking and reasoning" (p.88).

Personal epistemology: conceptual frameworks

There are several prominent conceptual frameworks within the field, and they differ in a number of respects; notably: what constitutes personal epistemology (e.g. Hammer & Elby, 2002; Schommer-Aikins, 2004; Sandoval, 2009), the relative emphasis placed on the aspects of personal epistemology (e.g. Greene, Azevedo & Torney-Purta, 2008; Greene, Torney-Purta, Azevedo & Robertson, 2010), the degree of 'inter-connectedness' of the elements at the psychological level (that is, how they are constructed in the mind) (e.g. Schommer-Aikins, 2004, c.f. Perry, 1970), the extent to which there is a 'developmental trajectory' (e.g. Perry 1970, c.f. Hammer & Elby, 2002), and the 'sensitivity' of the framework to context-dependency (e.g. Hammer & Elby, 2002, c.f. Schommer, 1990).

For present purposes, the differences between the conceptual frameworks can be largely eschewed without having a significant effect on the study (also see *The convergence of personal epistemology and nature of science*, below): the study does not engage to any significant extent with, for example, the nature of the underlying cognitive structures, nor does it engage with or produce data that can be used to address the number, type, or 'degree of inter-connectedness' of the elements (or 'dimensions'), that are posited to constitute personal epistemology. The aspect of personal epistemology that is relevant for present purposes is here formulated as a spectrum from 'rudimentary' to 'sophisticated', and this finds a rare instance of consensus across the conceptual frameworks, at least to a first approximation.

Positioning of an individual's personal epistemology along the 'rudimentary'-'sophisticated' spectrum is a judgment on the ability of that individual's personal epistemology to effectively and accurately construct knowledge and evaluate knowledge claims. The embedded systems model of Schommer-Aikins and colleagues proposes five, relatively independent, dimensions to personal epistemology: structure of knowledge (simple versus complex), stability of knowledge (fixed versus evolving), source of knowledge (authority versus 'reason'), speed of learning (gradual versus immediate) and ability (innate versus acquired) (Schommer, 1990; Schommer, 1994); a more 'sophisticated' personal epistemology would be one that recognises the structure of knowledge as complex, that employs 'reason' as a source, and conceives knowledge as constantly evolving. A similar model is that of Hofer and Pintrich (1997): an individual has a 'theory' of knowledge and knowing, and within this theory are four interconnected dimensions - certainty of knowledge, simplicity of knowledge , source of knowledge and justification of knowledge – with a distinction between rudimentary and sophisticated similar to that found in the embedded systems model.

There are conceptual frameworks that are more holistic in character - the dimensions are highly interconnected and covary – that also have a ‘rudimentary-sophisticated spectrum’ aspect. Perry’s (1970) scheme of intellectual and ethical development proposed nine stages, grouped into four categories, with progression from the ‘least sophisticated’ and culminating in the ‘most sophisticated’: from dualism, in which knowledge is derived from a single, authoritative source and is ‘true’; through multiplicity; then relativism; culminating in commitment to relativism: the acceptance of relativism and evaluative processes, the acknowledgement that refinement and change is unavoidable, and an increasing confidence in commitment to specific knowledge claims that exist in a wider population of claims. Two similar models are the reflective judgement model of King and Kitchener (1994) – in which progression occurs originating in the pre-reflective stage, advancing through the quasi-reflective stage and culminating in the reflective stage - and the framework of epistemological thinking by Kuhn (1999; see also Kuhn & Weinstock, 2002) – with progression from absolutism, through multiplism, to evaluativism.

Nature of science and scientific inquiry

Nature of science (NOS) and scientific inquiry (SI) tend to be terms more common to educational research, but these terms attempt to capture a ‘general narrative’ of science derived from science studies. According to Lederman et al. (2014), NOS “embodies what makes science different from other disciplines such as history or religion”, it “refers to the characteristics of scientific knowledge that are necessarily derived from how the knowledge is developed” (p.66); SI refers to “the processes of how scientists do their work and how the resulting scientific knowledge is generated and accepted” (p.66).

For NOS and SI, the relative emphasis of disagreement in the literature appears with what constitutes NOS and SI (Harrison, Duncan Seraphin, Philippoff, Vallin & Brandon, 2015). Prominent approaches to NOS and SI teaching are the ‘general aspects’ conceptualisations (see Lederman, 2007; Lederman et al., 2014; Kampourakis, 2016, see Table 1 below); these attempt to distil the nature of science in to a set of ‘aspects’ (properties, views, dimensions, themes, factors), that characterise the discipline of science. Science studies – especially the disciplines of philosophy of science, history of science, and sociology of science – have explored in extensive detail many aspects of science and scientific practice, and produced nuanced insights (e.g. Kuhn, 1962/2012; Merton, 1973; Biagioli, 1993; Godfrey-Smith, 2003; Ben-Ari, 2005; Shapin & Schaffer, 2011). However, a notable conclusion that has emerged, and that must be contended with when considering NOS and SI in educational research, is that it is difficult to ascertain exactly what science 'is': there is no single, agreed-upon, and explicated description of science; a list of necessary and sufficient characteristics has not been identified, and it is often necessary to introduce nuance and clarification for any properties that are identified. Recognition of this, in conjunction with practical considerations concerning placing NOS (and SI) in a classroom environment, has produced numerous challenges to the 'general aspect' approach, with the contention being that it simplifies and distorts both NOS and NOS teaching to an extent that it can produce misleading or erroneous conceptions (see Rudolph, 2000; Clough, 2008; Allchin, 2012; Matthews, 2012; Kampourakis, 2016). However, the 'general conceptions' approaches are popular in NOS and SI research, and a (non-exhaustive) set of aspects are collated here (see Table 1, next page) in order to provide some guidance for judgment of engagement with NOS and SI in the present study.

The convergence of personal epistemology and nature of science

Personal epistemology, NOS and SI can be brought together and considered within an educational setting. Sandoval (2005) adopts the term scientific epistemology in order to "focus particularly on students' ideas about the nature of scientific knowledge and the methods appropriate for generating and evaluating such knowledge" (p.638). This 'scientific personal epistemology' acknowledges the accumulating evidence of context-dependency of personal epistemological positions (e.g. Sandoval, 2005; Feucht, 2010; Bricker & Bell, 2016; Sandoval, Greene & Bråten, 2016), and that science entails its own unique network of epistemic values and practices.

Ideally, this context-specific personal epistemology and NOS components should be brought together into a single, coherent framework; however, as noted above, there is no consensus in either field. This has not gone unnoticed (e.g. Rudolph, 2000; Elby, 2009; Chandler & Proulx, 2010; Deng, Chen, Tsai & Chai, 2011; Lederman & Lederman, 2014; Sandoval et al., 2016), and the issue is how to proceed in *educational* research given the current situation.

General aspects	Reference
Scientific practice	
"Science produces, demands, and relies on empirical evidence".	McComas (2008, p.251) as cited in Kampourakis (2016, p.670).
Scientific knowledge is "empirically based (based on and/or derived from observations of the natural world)".	Lederman (2007, p.833).
"There is no one-way to do science and hence no universal, recipe-like, step-by-step scientific method can be followed".	Niaz (2009, p.23) as cited in Kampourakis (2016, p.670).
Scientists analyse and interpret data.	e.g. Osborne, Collins, Ratcliffe, Millar & Duschl (2003, p.713) as cited in Kampourakis (2016, p.670).
Accurate and methodical record-keeping is important.	e.g. Niaz (2009, p.23) as cited in Kampourakis (2016, p.670).
"Scientific knowledge relies heavily, but not entirely, on observation, experimental evidence, rational arguments, and scepticism".	Niaz (2009, p.23) as cited in Kampourakis (2016, p.670).
"Laws and theories are related but distinct kinds of scientific knowledge".	McComas (2008, p.251) as cited in Kampourakis (2016, p.670).
Observation and inference are important in science (and related but different).	e.g. Lederman (2007).
Formulating questions is important in science.	e.g. Lederman et al. (2014).
Hypotheses are important in science.	Osborne et al. (2003, p.713) as cited in Kampourakis (2016, p.670).
Critical testing is important in science.	Osborne et al. (2003, p.713) as cited in Kampourakis (2016, p.670).
'Theory-ladeness' in science.	e.g. Niaz (2009, p.23) as cited in Kampourakis (2016, p.670).
The 'properties' of scientific knowledge	
Science attempts to answer particular types of questions.	e.g. McComas (2008, p.251) as cited in Kampourakis (2016, p.670).
Science is self-correcting.	e.g. McComas (2008, p.251) as cited in Kampourakis (2016, p.670).
Scientific knowledge is tentative.	e.g. Lederman (2007, p.833).
Scientific knowledge is subjective.	e.g. Lederman (2007, p.833).
Personal and social elements of science	
Human imagination and creativity perform an important function in science.	e.g. Lederman (2007, p.833).
Science has a subjective element.	e.g. McComas (2008, p.251) as cited in Kampourakis (2016, p.670).
Pluralism in data interpretation.	e.g. Niaz (2009, p.23) as cited in Kampourakis (2016, p.670).
Shared ethos and norms in the scientific community.	e.g. Merton (1973); McComas (2008, p.251) as cited in Kampourakis (2016, p.670).
"Cooperation and collaboration in the development of scientific knowledge".	Osborne et al. (2003, p.713) as cited in Kampourakis (2016, p.670).
"Diversity of scientific thinking".	Osborne et al. (2003, p.713) as cited in Kampourakis (2016, p.670).
Scientific practice and knowledge, and the 'trajectory' of science, are all influenced by the social, cultural and historical context.	e.g. McComas (2008, p.251) as cited in Kampourakis (2016, p.670).

Table 1: General aspects NOS and SI

Regarding personal epistemology, Elby (2009) claimed that "it is more productive for the community *not* to converge on a definition until further empirical and theoretical progress points us toward the best way to carve cognitive structures at their joints" (p.19, emphasis original); a similar argument can be made for NOS and SI research: it may be worth 'probing' students' understanding, whilst recognising the current lack of a rigorous theoretical underpinning, "abandoning any notions of a universal `nature of science' and embracing the diversity of the particulars" (Rudolph, 2000, p.404).

Paralleling arguments put forward in the closely related field of biology (Mitchell, 2003), there may be value in adopting "integrative pluralism" in personal epistemology and NOS research (Dale, Dietrich & Chemero, 2009; Greeno, 2015): "different models with different theoretical bases allow researchers to discuss diverse relations between epistemic beliefs and cognitive processes" (Yang & Tsai, 2010, p.127), and "[o]ne's performance on a NOS assessment can simply be used to construct a profile of what the student knows/believes about scientific knowledge. … Different assessments may stress, to one degree or another, different aspects of NOS. … Different valid and reliable assessments stress and include different structures" (Lederman & Lederman, 2014, p.616). Therefore, as previously stated, the present study was not intended to be interpreted with reference to any particular personal epistemology framework, nor was it intended to appeal to any framework or conception of NOS or SI; the intention, then, was to establish some insight into the presence or absence of a SPE, and, if present, the extent to which students invoke their SPE, and what students articulate as part of their SPE, and to place this on a (rough-hewn) 'rudimentary'-'sophisticated' spectrum, determined by the degree of engagement with NOS.

Young learners' scientific personal epistemologies

Research suggests that 11-12 year-old students often have relatively unsophisticated SPEs: they may regard scientific knowledge as "a collection of true beliefs about concrete procedures", "basic facts", and "view scientific knowledge as accumulating in piecemeal fashion through simple telling or firsthand observation"; crucially, they may view scientific knowledge as "certain and true" and "experiments as providing certain information" (Smith, Maclin, Houghton & Hennessey, 2000). Khishfe (2008) drew similar conclusions: exploring 12-year-old (average age) students' views with respect to the tentative, empirical, creative and observation/inference-distinction aspects of NOS, they categorised the majority of students in the study as holding "naïve" views. Carey, Evans, Honda, Jay and Unger (1989) found that most 12-13 year-old students in the study held a "copy theory" of knowledge: knowledge is a faithful copy of the world that is imparted to the knower when the knower encounters the world" (p.526), and this can be considered to encompass a 'copying' through social learning. Further, students lack any real conception of 'theory-ladenness', or the inter-connectivity of evidence (Carey et al., 1989). An extensive review across several countries by Lederman et al. (2019) found that most students by the end of primary school have "mixed and naïve understandings" of aspects of scientific inquiry; students may be able to reasonably conduct important practices (such as repeating experiments), but did not express more than a superficial understanding of the purpose behind these practices.

It is possible that personal epistemology is biologically constrained, and, therefore, that there may be an age-dependent restriction on the 'sophistication' of an individual's personal epistemology. This position, which, according to Smith et al. (2000), has its roots in Piagetian child psychology, has become increasingly untenable: evidence from the child psychology literature supports the position that children have more substantial cognitive abilities than Piagetian psychology suggested (e.g. Halpenny & Pettersen, 2013).

Consistent with this, there is evidence that younger students can hold more sophisticated personal epistemologies (e.g. Feucht, 2017). For SPE, 'more sophisticated' conceptions are often found after intervention oriented towards facilitating an understanding of NOS and SI. Carey et al. (1989) used a constructivist approach, involving both abstract and concrete activities accompanied by an emphasis on metacognition with 12-year-old students, to facilitate students in moving from a 'level 1' (i.e. rudimentary) SPE to a more sophisticated conception in which "inquiry is guided by particular ideas and questions, and that experiments are tests of ideas" (p.527). Smith et al. (2000) found that students (11-12 years-old) could adopt "more sophisticated knowledge evaluation criteria" (p.386) and demonstrated a more nuanced understanding of the social nature of science. Although Khsihfe (2008) found most students held "naïve" views, after a 3 month 'intervention', students demonstrated a transition to more intermediary and then informed positions. Conley, Pintrich, Vekiri and Harrison (2004) found that, after a practical-oriented, student-led sequence of lessons, students (10-11 years old) developed a "more sophisticated" (p.198) view of source and certainty of knowledge. Research more specifically focusing on SI yields similar findings. For example, Lehrer, Schauble and Lucas (2008) found that, through correctly scaffolded, student-led, practical-oriented investigations, students (11-12 years old) developed a "more realistic conception" of NOS and SI (p.527); Leblebicioglu et al. (2017) drew similar conclusions from a 'science camp' intervention (11-13 year old).The present study is intended to provide some initial insight into the SPEs of Year 7 students (11- to 12-years-old).

Research questions

The overarching research question is: "What are the scientific personal epistemologies of students aged 11-12 (Year 7)?". The approach adopted for this study was to address three (sub) research questions – henceforth, simply research questions – which, in sequential order, attempt to construct from foundations an impression of students' SPEs. It is self-evident that an ability to cluster knowledge in a discipline-consistent fashion and to conceive – however accurately – of a discipline of science are *condiciones sine quibus non* for a SPE. These pre-requisites are the subjects of research questions one and two, respectively. The third and final research question attempts to gain some insight into the 'nature' of students' SPEs. These research questions are considered in more detail presently.

It was first necessary to establish if students could cluster knowledge in a discipline-consistent fashion. Being defined differentially gives a discipline 'substance', or meaning (e.g. Eagleton, 2008, chapter 4, for a related discussion). Ability (or inability) to cluster knowledge in a discipline-consistent way provides insight into students ability to construct a meaningful science discipline; the potential to have a conception of the discipline of science – and, therefore, a SPE – is contingent on the ability to cluster knowledge in a discipline-consistent fashion. From this, emerges the first question (research question 1; RQ1): how do students cluster knowledge?

If students can cluster knowledge in a discipline-consistent fashion, it is necessary to establish if students favour science as a means of addressing particular questions. This is fundamental to the differentiation of a discipline (see Eagleton, 2008), since its value stems, at least partially, from its privileged status in addressing particular questions and in constructing knowledge claims of a particular kind. It is, therefore, important to establish students' conceptions of the 'status' and the 'domain' of science. To some extent, the value of a discipline resides in its *preferential* selection. As such, the second question (RQ 2) is: do students appeal to science to address questions that have traditionally been addressed by both scientific and non-scientific disciplines?

The two preceding questions attempt to establish whether students have the conception of a science discipline. If students exhibit some conception of a science discipline, what are the associated personal epistemologies that students hold? The instruments used for the final question rely on self-report and there are a number of potential issues in using self-report in this fashion (notably, as Hofmann, Gawronski, Gschwendner, Le and Schmitt (2005) observe, "implicitly assessed representations may differ as to whether they are introspectively accessible for explicit self-report" (p.1370)). For this reason, a related but somewhat more limited question is posed, and the final question (RQ 3) of the study is, therefore: how do students *articulate* their SPEs?

Methodology and Methods

Table 2 (next page) provides the planning grid, outlining the data sources employed to respond to each of the research questions.

Methodology

Case-study

Case studies provide a research approach for exploring particular instances of a wider phenomenon, allowing for an in-depth exploration of the construct when realised in a natural setting (see Denscombe, 2017). The "'holistic' view" of the case study approach means that it is well-suited to investigating concepts that are multi-faceted with many and complex interacting factors (Denscombe, 2017, p.58). As such, it is well suited to SPE research, considering the multi-dimensional nature and context-dependency of the construct. For present purposes, the value of the case study is in its ability to produce descriptions of a construct when that construct occurs within a natural setting: the present study is concerned with students' SPEs (the construct) as they are (the natural setting).

One of the central issues with case studies is what Denscombe refers to as 'generalizability'; is the case study informative beyond the particular instance? Of concern for the present study is the external validity - what Denscombe (2017) refers to, approximately, as the 'transferability' -, since the present study is intended to capture a "typical instance" (p.60) of students' SPEs.

Overarching research question: What are the scientific personal epistemologies of students aged 11-12 (Year 7)?			
Research questions	**Data source 1**	**Data source 2**	**Data source 3**
RQ 1: How do students cluster knowledge?	Instrument 1 - Person A knows a lot about subject Y. Which of the following is A likely to know more about? The instrument is adapted from Danovitch and Keil (2004).		
RQ 2: Do students appeal to science to address questions that have traditionally been addressed by both scientific and non-scientific disciplines?	Instrument 2 - Whom would you ask? This instrument is influenced by studies into the division of cognitive labour (see Bromme, Kiehues & Porsch, 2010) and based on work in this field (e.g. Lutz & Keil, 2002).	Instrument 3 - Gorvald meets… This instrument was inspired by the VNOS-C questionnaire, question 1 (e.g. Lederman, Abd-El-Khalick, Bell and Schwartz, 2002), and was adapted to be more appropriate to Year 7 students.	Instrument 4 - Healing Crystals The instrument is not directly adapted from a pre-existing instrument. It was constructed from a consideration of the advantages of concept cartoons - they can encourage students' to be more open and speculative whilst simultaneously constraining discussion to the topic (Keogh & Naylor, 1999; Naylor, Keogh & Downing, 2007; Chin & Teou, 2009; Cavagnetto, 2010) -, the applications of concept cartoons in a similar fashion in NOS and SI research (e.g. Buffler, Lubben & Ibrahim, 2009; Suzuri-Hernandez, 2010), and demarcation as a "subject for inquiry, not a catechismal matter" (Matthews, 2012, p.12).
RQ 3: How do students articulate their scientific personal epistemologies?	Instrument 3 - Gorvald meets…	Instrument 4 - Healing Crystals	Instrument 5 - Views about scientific inquiry questionnaire, questions 1-3. From Lederman et al., (2014).

Table 2: Planning grid. Abbreviations are as follows:

Research Question – RQ; Nature of science – NOS; Scientific Inquiry – SI; Views of nature of science – VNOS

The instruments employed here are only intended to describe the SPEs, and do not provide insight into potential elements with which an individual's epistemology may interact; that is, although it acknowledges context, it does not explore context. This is, of course, a major limitation on the study in terms of addressing its generalisability. Further research would be necessary, both in identifying the necessary and sufficient elements of a personal epistemology network, and in characterising the 'epistemic climate' (both present and historical, see Feucht, 2010). The most that can be said for the present study in terms of external validity, is that the study is generalisable to the extent that the students participating in the study represent a typical cohort of students, with (at least) educational histories than can be considered 'typical'.

Details of the case

30 students (17 assigned male, 13 assigned female) aged 11-12 from a 'mixed-ability' Year 7 science class participated in the study. No students have an education and health care plan. 4 students require academic support: ADHD (1 student), "weak attainment" (2 students), "processing issues" (1 student), "weak decoding, reading and spelling skills" (1 student). The school is a mainstream, non-selective secondary school. Student anonymity was achieved through the random assignment of each student to an alias: 7A to 7Z for 26 students, and then 7AA to 7DD for the final 4 students.

Ethics

The study was considered to be in accordance with the British Educational Research Association's (BERA) ethical guidelines for educational research (2011). The study was approved by the subject mentor. The instruments were administered during allocated lesson time and consisted of a series of starter activities. Engagement with SPE is a component of the national curriculum at key stage 3, and research suggests that it is beneficial to science learning; as such, the intervention was considered to be at least inert with respect to student learning. Participants were informed that their responses would be anonymised, that participation is voluntary, that the results do not contribute to their recorded grades, and that answers are subjective (i.e. there are no correct responses). As one question entailed a consideration of both science and religion, both the voluntary participation and the subjectivity of responses was emphasised when conducting this instrument, and participants were explicitly informed that the questions are not intended to make any judgement on either science or religion, or intended to suggest superiority of any discipline.

Methods

This section provides an outline of each of the data collection instruments and approaches to data analysis that were employed.

Instrument 1 - Person A knows a lot about subject Y. Which of the following is A likely to know more about?

This instrument is intended to investigate how students cluster knowledge (RQ 1). There are eight questions. Each question introduces a person who is described as knowledgeable about a specific subject/phenomenon (lead statement) and then provides a multiple-choice list of statements (response statement) (see Table 3). The response statements may be related to the lead statement in a number of ways: they may share topic, discipline, goal, or no connection (more than one connection is possible). For present purposes, the concern is with discipline-consistent knowledge clustering. Disciplines are, fundamentally, social constructs, but emerge from "complex relational structures" (Danovitch & Keil, 2004, p.920), forming a community, body of knowledge, practices and values in pursuit of the study of a particular aspect of the natural or social world; for example, physics and psychology are both disciplines (Danovitch & Keil, 2004 provide further insight into this subject). This instrument is considered to be 'more abstract' than the *Whom would you ask?* instrument (see below), as it requires deciphering the nature of the knowledge within both the lead statement and each response statement and relating them appropriately. The instrument is adapted from Danovitch and Keil (2004).

Instrument 2 - Whom would you ask?

This instrument is intended to investigate if students recognise the subject of a scenario and identify an appropriate profession/discipline, with an accompanying justification (RQ 2). There are twelve questions. Each presents a scenario that can be informed by a contribution from a professional of a given discipline, followed by asking the participant to identify "whom would you ask?" to inform the scenario; students could choose more than one profession/discipline, and were asked to justify, if possible, their decision.

1. Some plants are modified in a lab to make them produce more food. Bob knows a lot about why plants need sunlight. Which of the following is Bob more likely to know about?	
If modified plants are a good idea or a bad idea.	Topic
What the best soil for growing plants is.	Discipline
2. Michelle knows more about why tennis balls bounce better on the playground than on the grass. Which of the following is Michelle more likely to know about?	
a) Why bubble wrap keeps glass things from breaking.	Discipline
b) Why tennis balls come in cans of three.	Topic
c) Why orange tennis balls are easier to see in the grass than green ones.	Topic and Goal
3. John knows a lot about why large marbles make small marbles go farther when they bump into them. Which of the following is John more likely to know about?	
a) Why a hammer drives a nail better if you swing the hammer faster.	Discipline
b) Why marbles were first made in ancient Egypt.	Topic
c) Why it is hard to keep track of marbles while they are moving around.	Topic and Goal
4. Janet knows a lot about how to calculate the areas of shapes. Which of the following is Janet more likely to know about?	
a) How to solve the equation $2x = 3$	Topic and Discipline
b) Why the number 13 is considered unlucky.	Topic
5. Nicola knows a lot about why Britain became involved in the Second World War. Which of the following is Nicola most likely to know about?	
a) Why people are sometimes aggressive towards each other.	Topic
b) Why the atomic bombs caused more damage than the more conventional bombs.	Topic
c) Why Germany surrendered in 1945.	Topic and Discipline
6. Paul knows a lot about why airplanes need one wing on each side to fly. Which of the following is Paul likely to know more about?	
a) Why airplanes are usually made in the United States.	n/a
b) Why birds build their nests in the spring.	n/a
7. Maria knows a lot about why keys do not work as well if they are old and worn out. Which of the following is Maria likely to know more about?	
a) It is hard to turn the wheels on a bicycle if they are rusty.	Discipline
b) Keys were first used in ancient Rome.	Topic
c) People sometimes forget which keys open the front door to their house.	Topic and Goal
8. Lea knows a lot about why ancient Celts – people who lived in Britain a long time ago – buried jewellery with family members when they passed away. Which of the following is Lea likely to know more about?	
a) Why the soil of ancient gravesites is different to soil where there aren't any gravesites.	Topic
b) Why Roman emperors used to pay for large festivals to be held in Rome.	Discipline
c) Why a lot of people enjoy eating chocolate.	n/a

Table 3: Person A knows a lot about…

Three of the twelve questions (the 'key questions') can be interpreted as a judgement on whether students appeal to science – or practitioners of science and science-related disciplines - to answer questions that have traditionally been addressed by both scientific and non-scientific disciplines (see

Table 4). This instrument is influenced by studies into the division of cognitive labour (see Bromme, Kiehues & Porsch, 2010) and based on work in this field (e.g. Lutz & Keil, 2002).

1. My car has broken down, and I want to know what is wrong with it. Whom should I ask?	
2. I want to know what causes the tides of the oceans. Whom should I ask?	
3. You want to paint a picture of a sunset, and you want to know what are the best colours to use. Whom would you ask?	
4. You want to know where human beings came from. Whom would you ask?	Key question
5. You want to know how many sides a dodecahedron has. Whom would you ask?	
6. You want to know whether you can play in an abandoned factory. Whom would you ask?	
7. You want to know where the universe came from. Whom would you ask?	Key question
8. You want to know why humans experience pain. Whom would you ask?	
9. You are reading the Bible, and you want to know what the following passage means: "Love never fails. But where there are prophecies, the will cease; where there are tongues, they will be stilled; where there is knowledge, it will pass away." Whom would you ask?	
10. You want to make a paper plane to goes really far. You need to know what the best design would be. Whom would you ask?	
11. You are in a competition to build the tallest tower using only one hundred blocks. You want to know what the best method is. Whom would you ask?	
12. Your friend believes that they saw a spirit. You want to know whether this is possible. Whom would you ask?	Key question

Table 4: Whom would you ask?

Instrument 3 - Gorvald meets…

This is a free-form method to allow students the opportunity to explain their conception of science and religion; this instrument was employed to provide insight into RQ 2 and RQ 3. There are two cartoon illustrations of Gorvald, an alien visitor to earth; in one illustration, Gorvald meets with a scientist, and in the other, a theologian (see Figures 1 and 2). Gorvald asks the interlocutor to explain their profession. It attempts to be sensitive to professional versus classroom personal-epistemology context-dependency by encouraging students to 'imagine' themselves in the relevant profession (see Sandoval, 2005). The choice of professions is based on the different epistemic values and practices for each discipline. A number of NOS and SI questionnaires adopt a similar approach, both in the context of interviews and written questionnaires; this instrument was inspired by the VNOS-C questionnaire question 1 (e.g. Lederman et al., 2002), and was adapted to be more appropriate to Year 7 students. The cartoon illustrations and accompanying text were of the author's own creation.

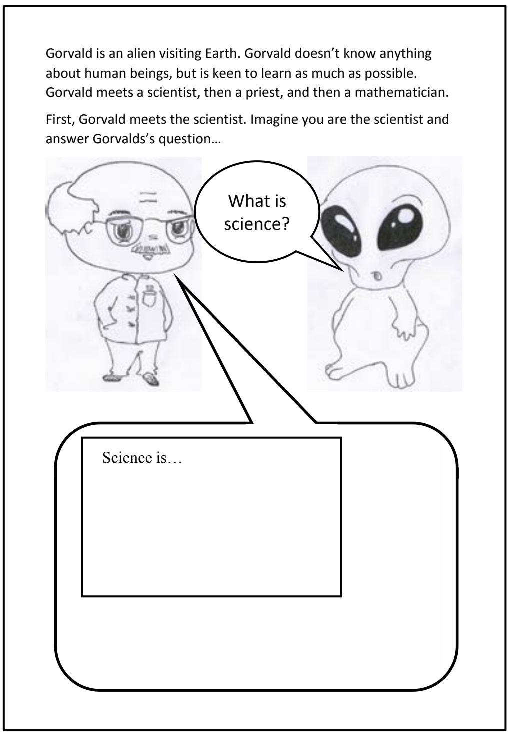

Figure 1: Gorvald meets a scientist

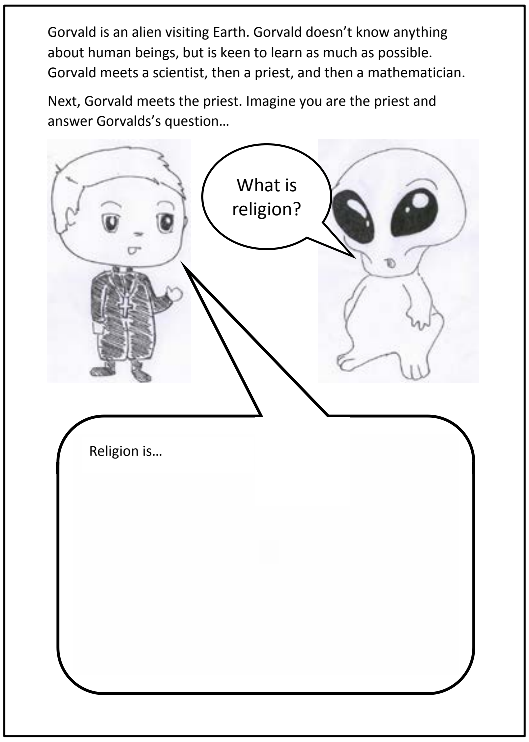

Figure 2: Gorvald meets a priest

Instrument 4 - Healing Crystals

A concept cartoon in which four friends are discussing questions in science. The instrument has two questions (see Figure 3). The intention of the first question is to explore students' beliefs regarding the types of questions that science can address, using crystal healing as a scaffold. The second question is to elucidate respondents' understanding of the term "scientific evidence". This instrument was employed to provide insight into RQ 2 and RQ 3. The instrument is not *directly* adapted from a pre-existing instrument. It was constructed from a consideration of the advantages of concept cartoons – they can encourage students to be more open and speculative whilst simultaneously constraining discussion to the topic (Keogh & Naylor, 1999; Naylor, Keogh & Downing, 2007; Chin & Teou, 2009; Cavagnetto, 2010), the applications of concept cartoons in a similar fashion in NOS and SI research (e.g. Buffler, Lubben & Ibrahim, 2009; Suzuri-Hernandez, 2010), and demarcation as a "subject for inquiry, not a catechismal matter" (Matthews, 2012, p.12). The cartoon illustration and accompanying text were of the author's own creation.

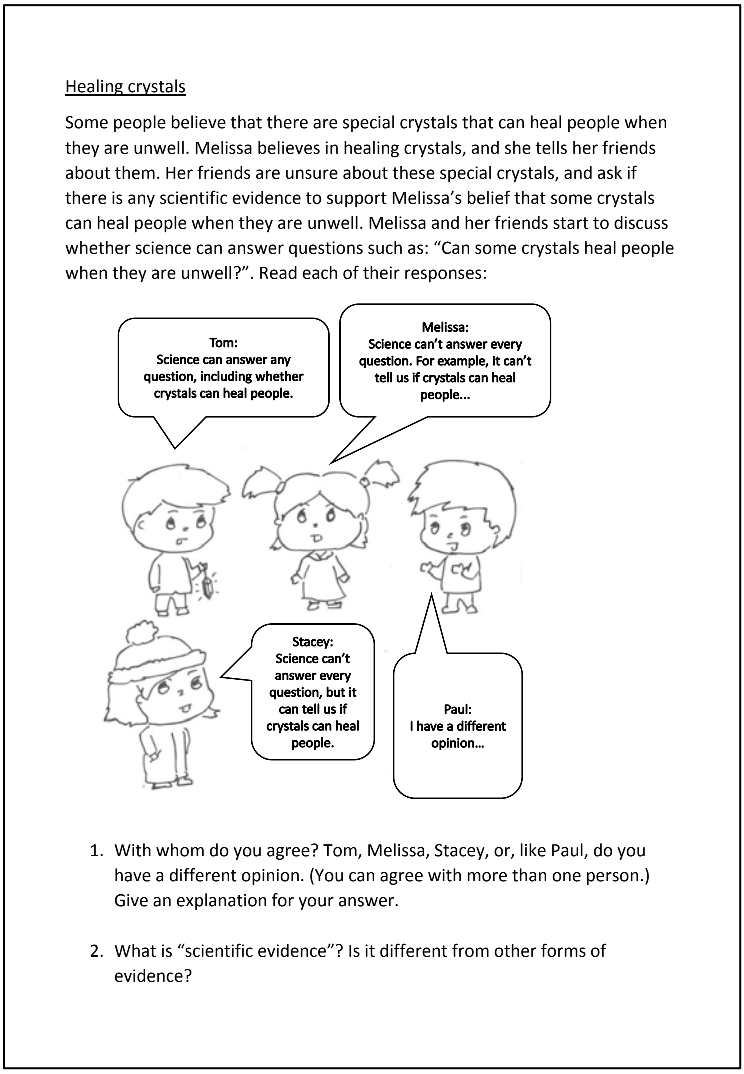

Figure 3: Healing Crystals

Instrument 5 – Views about scientific inquiry (VASI) questionnaire, questions 1-3.

This consists of three questions that attempt to engage students in a consideration of scientific inquiry (see Table 5). This is a well-established questionnaire that is frequently employed to probe students understanding of scientific inquiry (Lederman et al., 2014), and was employed to provide insight into RQ 3. Questionnaires can provide some degree of standardisation, and can reduce interpersonal factors, such as interviewer effect; this may be particularly important considering the teacher-student relationship is, in a standard classroom setting, to some extent characterised by students being conditioned to provide responses 'approved of' by teachers. The main issue is internal validity, such as content validity (e.g. Drost, 2011); interpretation of questions is a much-discussed issue in personal epistemology and NOS research (e.g. Lederman, 2007; Allchin, 2011; Mason, 2016; Sandoval et al., 2016). However, the VASI questionnaire is frequently used, and has been subject to testing in this regard (Lederman et al., 2014; Lederman et al., 2019).

Question	**Targeted aspects of SI**
1. A person interested in birds looked at hundreds of different types of birds who eat different types of food. He noticed that birds who eat similar types of food, tended to have similar shaped beaks. For example, birds that eat hard-shelled nuts have short, strong beaks, and birds that eat insects have long, slim beaks. He wondered if the shape of a bird's beak was related to the type of food the bird eats and he began to collect data to answer that question. He concluded that there is a relationship between beak shape and the type of food birds eat. (a) Do you consider this person's investigation to be scientific? Please explain why or why not. (b) Do you consider this person's investigation to be an experiment? Please explain why or why not. (c) Do you think that scientific investigations can follow more than one method? If no, please explain why there is only one way to conduct a scientific investigation. If yes, please describe two investigations that follow different methods, and explain how the methods differ and how they can still be considered scientific.	Scientific investigations all begin with a question but do not necessarily test a hypothesis. There is no single set and sequence of steps followed in all scientific investigations (i.e., there is no single scientific method).
2. Two students are asked if scientific investigations must always begin with a scientific question. One of the students says "yes" while the other says "no". Whom do you agree with and why?	Scientific investigations all begin with a question but do not necessarily test a hypothesis.
3. (a) If several scientists ask the *same question* and follow the *same procedures* to collect data, will they necessarily come to the *same conclusions*? Explain why or why not. (b) If several scientists ask the *same question* and follow *different procedures* to collect data, will they necessarily come to the same conclusions? Explain why or why not.	All scientists performing the same procedures may not get the same conclusions. Inquiry procedures can influence the conclusions.

Table 5: VASI questionnaire, questions 1-3 (adapted from Lederman et al., 2014)

Data analysis

The content analysis of data obtained from the instruments consisted of two sequential processes: coding and category generation. Each 'response' (i.e. the entirety of each individual participant's response to a given question) was treated separately; each response corresponds to a participant.

The coding process was approximately that of an inductive content analysis approach (e.g. Thomas, 2006; Elo & Kyngäs, 2007; for a general overview of methods, see Cohen, Manion & Morrison, 2011). In the coding process, responses were analysed for the presence of individual 'meaning units', with units being identified based on the interpretation by the researcher of contiguous or non-contiguous sections (or the entirety) of the response as conveying a single meaning. Each response may contain more than one meaning unit. Each meaning unit was then condensed to facilitate coding; this consisted of removing and rephrasing sections of the meaning unit.

The next stage was to transform the condensed meaning unit into a code. Codes attempt to capture the essential elements of the meaning unit, and were partially constructed using keywords derived from meaning units across responses; this latter process facilitates category formation.

The final stage was category formation. In this process, codes are considered in relation to each other and clustered based on a judgement of difference, similarity, and frequency of occurrence. An additional process involved in category generation was included that approximates deductive content analysis (e.g. Elo & Kygäs, 2007; Forman & Damschroder, 2008). The categories produced in the process of category generation were considered in relation to themes prevalent in personal epistemology, NOS (and SI) research (e.g. see Table 1). That is, an attempt was made, when translating codes into categories, to construct categories more amenable to analysis in relation to personal epistemology and NOS.

Two notable categories that were constructed were based on codes generated on the basis of a comparison of codes between the *Gorvald meets…* questions, producing the categories of "Non-overlapping magisteria, science and religion (ill-defined)"and "Over-lapping magisteria, science and religion (ill-defined)". Assignment to these categories is based on the presence of codes in one or more of a participant's responses that suggests that there is or there is not a distinction in the epistemic values or practices between science and religion, respectively (for more detail on the 'non-overlapping magisteria' concept, see Gould, 1999).

Figure 4 provides an example of the coding analysis process. Consider the response: "Science is a way of discovering questions and answers and experimenting to find a good answer". This response contains two meaning units, one of which is "experimenting to find a good answer". This forms the condensed meaning unit: "experiments find good answers". From this, and from a consideration of other meaning units, the code "Experimentation can generate reliable knowledge claims" is formed, containing a keyword ("Experimentation") and an additional component that retains some degree of the complexity present in the meaning unit. The second response in Figure 4, "Science is experimenting to find out if something is true or false", is transformed through the same process into the code: "Experimentation determines the veracity of knowledge claims".

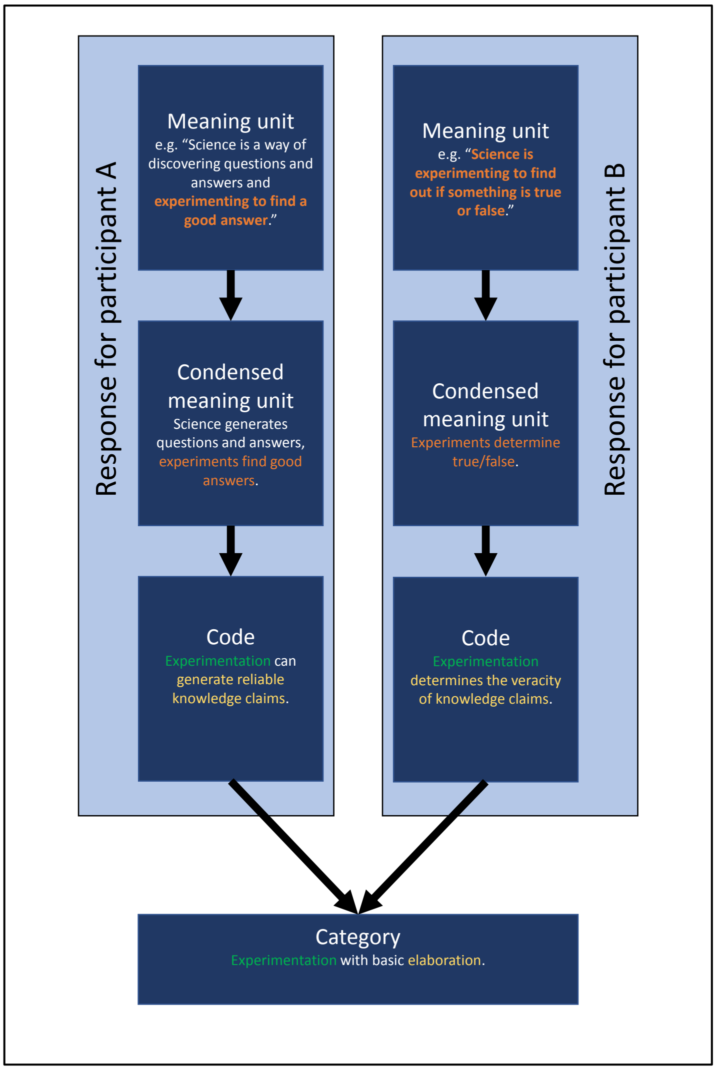

Figure 4: Coding example

These codes, although different, can be abstracted to form a category of "Experimentation with basic elaboration". This may be contrasted with meaning units that simply state that, for example, "science is experiments", which in the transformation to a code would include the keyword "Experimentation", but no suggestion of complexity; thus, two categories are produced: "Experimentation" (in this case, sharing the name of the code), and "Experimentation with elaboration", acknowledging differences in complexity of meaning units (and suggestive of differences in complexity of students' scientific personal epistemologies).

There are two impulsions at variance in the coding process: towards generalisation and a preservation of uniqueness. The purpose was to translate the language into a more analyticallyaccessible form, yet would minimise information loss in the conversion – information that may suggest degrees of complexity in students' SPEs. The abstraction to categories functions to cluster meaning units across participants, facilitating analysis and the identification of 'general narratives'; it also mitigates over-interpretation of meaning units, which should improve the external validity. However, there was a sensitivity to 'unique accounts', nuance, and elaborations in the coding process that influenced category formation. A balance must be achieved through researcher judgement (i.e. there is a subjective element to the process, e.g. Thomas, 2006).

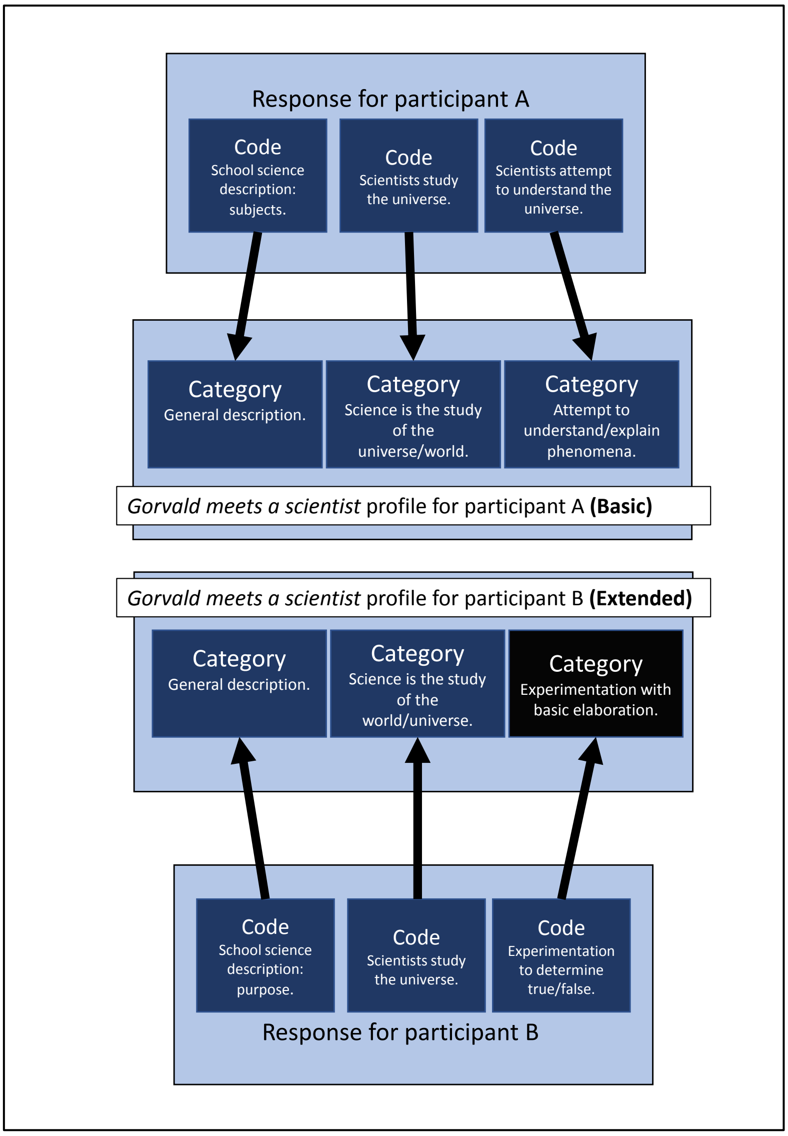

Figure 5: Examples of profile generation

After category generation was complete, profiles were constructed. A profile is constructed for each response from a participant for a particular instrument, instrument question, or instrument sub-question. A profile is characterised by the set of categories that it contains, or is 'labelled' with (see Figure 5). In this way, categories could be considered for analysis (predominantly prevalence), and profiles for each response (i.e. participant) could be considered for analysis, including the comparison of profiles or their clustering if they share commonalities; this latter function was used to differentiate between "Basic" and "Extended" profiles (see below).

In Figure 5 the presence of "Experimentation with basic elaboration" category in the profile for participant B identifies that profile as "Extended".

Basic and Extended meta-categories

For each instrument, or questions within instruments, two ‘meta-categories’ were created: “Basic” and “Extended”. The motivation for construction of the Basic and Extended categories – different for each instrument or question, as appropriate – was to make a distinction between profiles that represented only a *relatively* superficial, general SPE, and profiles that included categories that represented a *relatively* ‘extended’ SPE: “Basic” and “Extended”, respectively. This should facilitate analysis of the results: providing some insight into the ‘depth of engagement’ with SPE.

Assignment to one of these two meta-categories was based on the presence or absence of categories within the responses’ profiles. The following criteria was used to identify Extended profiles:

Criteria i) Included categories that engaged with topics beyond that of the ‘group standard’ as determined by a comparison across profiles, with a further filtering of these atypical profiles based on a judgement that the categories that distinguished these profiles as atypical also *approached* engagement with topics relevant to SPE.

Criteria ii) Included categories that distinguished these profiles based on a (relatively) more sophisticated conception of NOS and SI.

Use of Extended profiles acknowledges an elaboration in a response and avoids as much as is reasonably possible a consideration of the ‘correctness’ of the elaboration. For example, “observation as experiment” suggests an elaboration, but may not be correct use of scientific terminology.

Results

Instrument 1

Person A knows a lot about subject Y. Which of the following is A likely to know more about?

Analysis of the data (N = 21) consisted of making a distinction between discipline and non-discipline choices (see Table 3). Approximately 25% of participants responded in a discipline-consistent way – that is, choosing responses statements that are discipline-based as oppose to goal- or topic-based – on approximately 35% or less of the questions, 50% of the participants respond in a discipline-consistent way on approximately 50% or less of the questions, 75% respond in a discipline-consistent way on approximately 70% or less of the questions, and 100% responds in a discipline-consistent way on 90% or less of the questions (see Figure 6). There is a lack of uniformity for students aged 11-12 in clustering knowledge according to discipline: there is a fairly even spread in terms of the proportion of responses to which students offer a discipline-consistent response (see Figure 6), suggesting perhaps a nebulous conception of a science discipline, or 'domain of science'.

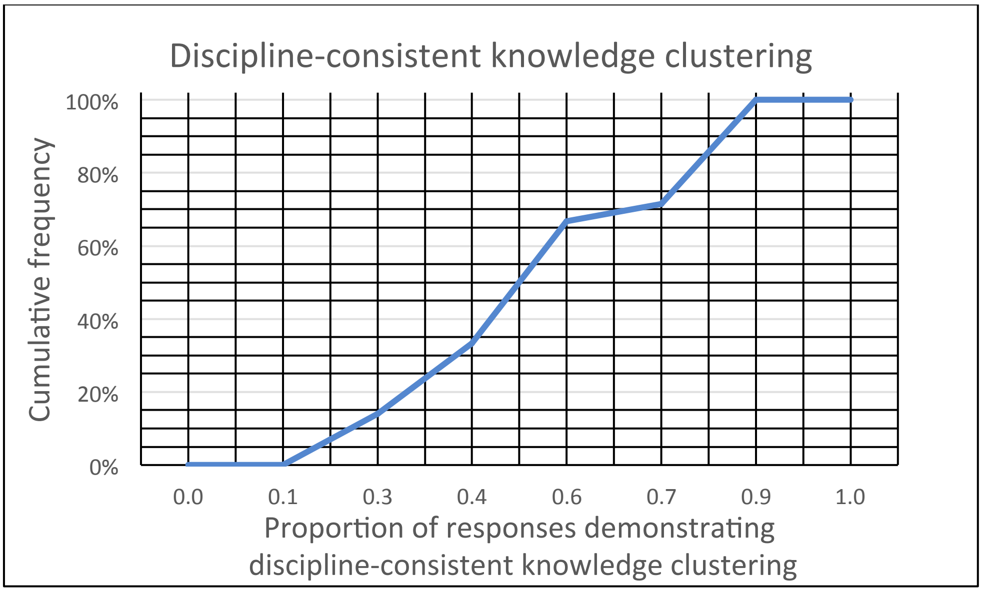

Figure 6: *If A knows…* Cumulative frequency graph for knowledge-based clustering

Instrument 2

Whom would you ask?

Participants had little difficulty in assigning familiar and reasonable professions with accompanying justifications. Considering the three questions that could provide insight into students' conception of the 'province' of science (the key questions), the justifications were too varied, brief, or tautologous to permit any reasonable coding. No participant routinely provided a non-science profession to address these questions; answers were either mixed (science and non-science), or 'science-oriented'. The data was analysed for participants who had responded to at least two of the key questions (N = 18), and again for students who had responded to all three of the key questions (N = 7) (see Figure 7). For at least two key questions answered: 0% gave all non-science-oriented responses, 28% gave mixed responses, and 72% gave science-oriented responses. For all three key questions answered: 0% gave all non-science-oriented responses, 43% mixed responses, and 57%

science-oriented responses. These results suggest that students appeal preferentially to science to address questions that have traditionally been addressed by both scientific and non-scientific disciplines.

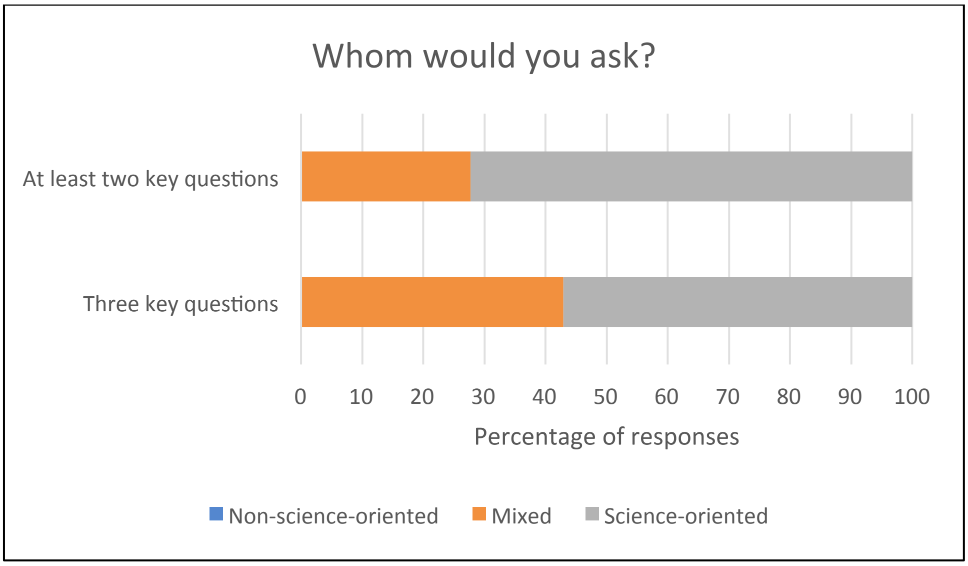

Figure 7: *Whom would you ask?* Proportional bar charts for at least two key questions answered (top) and all three key questions answered (bottom)

Instrument 3

Gorvald meets…

Content analysis of the *Gorvald meets…* did not produce evidence of any *meaningful* engagement with aspects of personal epistemology, NOS or SI for all participants, and that the demarcation of science from non-science, at least as articulated, is relatively unrefined. There are some indications, more evident from the Basic and Extended meta-categorisation (see below), of a superficial engagement with aspects of SPE. 22 responses were analysed for *Gorvald meets a scientist* (N_S = 22), 21 for *Gorvald meets a priest* (N = 21); see *Data analysis* (above) for the coding process.

Common categories that emerged for science were: "General Description (50%)", "Science is the study of the universe/world" (36%), "Science entails discovery" (27%), "Attempt to understand/explain phenomena" (23%) and "How/what (as oppose to why)" (14%). Less frequent categories that emerged: "Experimentation with basic elaboration" (10%), "Experimentation (no elaboration)" (9%), "Science involves constructing knowledge (ill-defined)" (5%), and "Science is a human practice" (5%). Table 6 provides category and associated meaning unit examples.

Categories	Meaning unit(s) examples
General description	"There are chemistry, Biology and physics." – Student 7DD "Science is where you learn about the earth and world." – Student 7A
Science is the study of the universe/world	"Science is the study of the universe…" – Student 7R "The study of everything that happens in the universe" – Student 7Y
Science entails discovery	"Where you descover more things" – Student 7Z
Experimentation (no elaboration)	"Science is – working-out experimenting" – Student 7P
Experimentation with basic elaboration	"Science is experiments to find out if something is true or false." – Student 7C "Science … [includes] experimenting to find a good answer." – Student 7T
Attempt to understand/explain phenomena	"…science is a way to explain what happens around the world, or even the universe." – Student 7F "…explanations of how things are made like the sun and particles, we do it for explanations…"
How (as oppose to why)	"Science is everything about 'how', if you ask any question with the word how in the answer is to do with science" – Student 7BB "… religion is a way to explain why everything happens…", c.f. "… science is a way to explain what happens around the world … a way to explain what things are made out of, what things do and what the reaction is when that is happening" – Student 7F ['what' is considered to approximate 'how', here]
Science involves constructing knowledge (ill-defined)	"Science is a way of discovering questions and awnsers and experimenting to find a good awnser" – Student 7T
Science is a human practice	"They [i.e. scientists] do it [i.e. science] because humans like to know why they are on earth and why things happen." – Student 7R

Table 6: Examples of coding categories and associated meaning units for Gorvald meets a scientist

Common categories that emerged for religion were: "General description (57%)", "Belief (ill-defined)" (67%), and "Deity influences the function of the universe/world" (24%). Less frequent categories that emerged: "Religion governs ethics (no corresponding claim for science)" (10%), "Why (as oppose to 'how'/'what')" (5%), "Religion is a human construct" (5%), and "Religion is not evidence-based" (5%). Table 7 provides some examples of coding categories and associated meaning units for Gorvald meets a priest.

Categories	Meaning unit(s) examples
General description	"There are Christianity, Muslims, Sikes [Sikhs] and lots more." – Student 7DD "Religion is a group of people that follow a certain thing to do with god." – Student 7J
Belief (ill-defined)	"Religion is what people believe in…" – Student 7B "Religion is a belief in something…" – Student 7K
Deity influences the function of the universe/world	"… God … operates the world and the universe…" – Student 7F
Religion governs ethics (no corresponding claim for science)	"Religion is a belief that a human may have with rules on how to live their lives" – Student 7BB
Why (as oppose to 'how'/'what') *Some form of distinction that suggests religion is concerned with moral/philosophical questions ('why' questions) and science is concerned with natural-world questions ('how' questions)*	"… religion is a way to explain why everything happens…", c.f. "… science is a way to explain what happens around the world … a way to explain what things are made out of, what things do and what the reaction is when that is happening" – Student 7F
Religion is a human construct	"Religion is something people made up through history" – Student 7E
Religion is not evidence-based	"There is no evidence for what is in a religeon." – Student 7K

Table 7: Examples of coding categories and associated meaning units for Gorvald meets a priest

From a comparison of the science and religion responses, 14% of responses were categorised as "Over-lapping magisteria, science and religion (ill-defined)" and 19% as "Non-over-lapping magisteria, science and religion (ill-defined)": a comparison of meaning units for science and religion responses suggested some indication that science and religion either did not, or did, respectively, constitute separate domains, to some extent (for the concept of non-overlapping magisterial, see Gould, 1999). Table 8 shows example associated meaning units for this category.

Category	Meaning unit(s) examples
Non-overlapping magisteria, science and religion (ill-defined)	"Religious people claim that … God made the earth. Some scientists however believe the big bang created the earth. Others believe that god made the big bang which created the earth." – Student 7BB "… religion is a way to explain why everything happens…", c.f. "… science is a way to explain what happens around the world … a way to explain what things are made out of, what things do and what the reaction is when that is happening" – Student 7F

Table 8: Non-overlapping magisteria category and associated example meaning units

Basic and Extended profiles for Gorvald meets a scientist

The Basic and Extended profiles make a distinction between profiles that represent only a *relatively* superficial, general description of the subjects, and profiles that included categories that 'extended' this general description: "Basic" and "Extended", respectively (see *Basic and Extended meta-categories*, above). Table 9 shows the categories used to construct an Extended profile for *Gorvald meets a scientist*. Criteria i (see *Basic and Extended meta-categories*, above) predominantly contributes to the construction of the profiles for the *Gorvald meets…* instruments.

Basic	**Extended**
General description Science is the study of the world/universe Attempt to understand/explain phenomena	Experimentation (no elaboration) Experimentation with basic elaboration Science entails discovery How (as oppose to why) Science has practical applications Science involves constructing knowledge (ill-defined) Science is a human practice
Percentage of Basic and Extended profiles	
48%	52%

Table 9: Gorvald meets a scientist, Basic and Extended categories

Basic and Extended profiles for Gorvald meets a priest

Table 10 shows the categories used to construct an extended profile for *Gorvald meets a priest*.

Basic	**Extended**
General description Belief (ill-defined) Deity influences the function of the universe/world	Religion governs ethics (no corresponding claim for science) Why (as oppose to how/what) Religion is a human construct Religion is not evidence-based
Percentage of Basic and Extended profiles	
77%	23%

Table 10: Gorvald meets a priest, Basic and Extended categories

Instrument 4
Healing Crystals

Content analysis of the *Healing Crystals* instrument did not produce evidence of any *meaningful* engagement with aspects of personal epistemology, NOS or SI for all participants; there is some indication of a domain of science that emerges from the data. 22 participants (N = 22) provided responses for question 1 of the instrument, and 17 for question 2 of the instrument.

Of the responses to question 1, 9% were "Tautological (at least in part)"; 14% of respondents "Agreed with Tom" (science can answer all questions), and 14% did not explicitly reference Tom (or agreement was unclear), but could be categorised as "Science can answer all questions". 32% "Agreed with Stacey" (Science can answer some questions, including if crystals can heal people), and 18% did not explicitly reference Stacey (or agreement was unclear), but could be categorised as "Science can answer some questions". 0% of responses were categorised as "Agreed with Melissa". 9% "Agreed with Paul" (Different opinion). 14% of responses contained meaning units that demonstrated some evidence of a distinction and were categorised as "Scientific/non-scientific question distinction". 5% could be categorised as "Science can answer questions that can be subject to experimentation". Table 11 provides category and associated meaning unit examples.

Categories	**Meaning unit(s) examples**
Scientific/non-scientific question distinction *Some evidence of a distinction*	"Types of questions that science can answer are like to do with the earth/space, humans, weather, nature, behaviour, and more… Questions that science cannot answer are thins about family/relitives, private things and more." – Student 7I "Science can work out how many mm the sea is increasing by, but they cant workout whats the meaning of life." – Student 7CC
Tautological (at least in part)	"Science can answer many questions but they need to be scientific." – Student 7G
Science can answer all questions	"… science can answer anything…" – Student 7Q
Science can answer some questions *There may or may not be explicit reference to the Healing Crystals example*	"I agree with Tom and Stacey [unclear agreement] because I think science can answer almost all questions about why thing/object/forces/body parts do what they do. Science can't tell us why people wear certain clothes or why you have a particular name, because the answers to the questions would be something like because their faviorit colour is red or because their parents like the name." – Student 7Y
Science can answer questions that can be subject to experimentation	"… questions science can answer are questions that people can experiment on and get results for, so if you could experiment on a crystal to see if it kills people or heal them science can answer the question…" – Student 7L

Table 11: Examples of coding categories and associated meaning units for Healing Crystals, question 1

Of the responses to question 2, 59% were "Tautological (at least in part)", and 6% were categorised as "Unclear". 12% were categorised as "Depends on experimental results", and 6% as "Depends on trial-and-error" (interpreted as experimentation). 6% were categorised as "Depends on scientific reason (ill-defined)”. 5% of responses contained meaning units that suggested scientific evidence is evidence that is “Unchangeable”. 6% of responses were categorised as “No distinction”. 6% were assigned to “Entails scientific practice (ill-defined)”. See Table 12.

Categories	**Meaning unit(s) examples**
Entails scientific practice *Some indication that scientific practice is distinct*	“Scientific evidence is something that is proved … in a scientific environment by someone who is practised in finding scientific evidence.” – Student 7K
Unchangeable	“There can be beliefs, but if the answer is changed by those, it isn’t propperly scientific.” – Student 7N
Depends on scientific reason (ill-defined)	“Scientific evedence is evedence backed up with a scientific reason.” – Student 7Y
No distinction	“… scientific evidence is any type of evidence as science is everything even if it is not discovered.” – Student 7T
Depends on trial-and-error	“Scientific evidence is evidence from trial-and-error” – Student 7N
Depends on experimental results	“Experiments and scientific data.” – Student 7G
Tautological (at least in part)	“Experiments and scientific data, it [i.e. scientific evidence] is different than others because they are scientific.” – Student 7I

Table 12: Examples of coding categories and associated meaning units for Healing Crystals, question 2

Basic and Extended profiles for Healing Crystals

Table 13 shows the categories used to construct an extended profile for *Healing Crystals*.

Question 1	
Basic	**Extended**
Tautological (at least in part) Agreed with Tom Science can answer all questions	Agreed with Stacey Science can answer some questions Scientific/non-scientific question distinction Science can answer questions that can be subject to experimentation
Question 2	
Basic	**Extended**
Tautological (at least in part) Unchangeable No distinction	Depends on scientific reason (ill-defined) Depends on experimental results Depends on trial-and-error Entails scientific practice (ill-defined)
Percentage of Basic and Extended profiles	
50%	50%

Table 13: Healing Crystals, Basic and Extended categories

Note that *Healing Crystals* draws on Criteria ii from section *Basic and Extended meta-categories*; Basic and Extended profiles are distinguished based on their closeness to a more sophisticated conception of NOS and SI, with Extended approaching a more sophisticated conception.

Instrument 5

VASI questionnaire

Content analysis did not produce evidence of any *significant engagement* with SPE; however, more evident from the Basic and Extended meta-category analysis (see below), there are some instances where meaning units suggested a tentative engagement with SPE, more so than with other, similar instruments used in the study. The first three questions of the VASI questionnaire were used (Lederman et al., 2014; see Table 4) .The number of respondents for each question are as follows: for question 1a, N = 19; 1b, N = 20; 1c, N = 17; question 2, N = 19; question 3a, N = 20; question 3b, N = 18.

From content analysis of question 1a, 63% of responses were categorised as "It was scientific (no elaboration or non-sequitur)"; that is, respondents considered the investigation to be scientific, but there was no further elaboration on this claim or it was difficult to deduce from the associated meaning units what the justification was or how it related to the claim. Other categories included: "All investigations are scientific" (11%) and "No, requires intervention" (5%). Two notable categories that emerged were: "It was scientific, involves data collection" (16%), and "It was scientific, involves problem-solving" (11%). 95% of the responses were categorised as "Rudimentary", the other 5% were considered to engage, albeit in a limited fashion, with SPE; these latter responses were also categorised as "It was scientific, involves problem-solving" (elaborated in the discussion). Table 14 provides category and associated meaning unit examples.

For question 1b, 25% were categorised as "Not an experiment, no intervention", 15% as "It was an experiment, involves data collection", 5% a "It was an experiment, involves problem-solving", and 10% as "It was an experiment, involves observation". 80% of responses categorised as "Not an experiment, no intervention" were also categorised as "It was scientific…" for question 1a. Further categories include: "Yes (unclear/no elaboration)" (25%), "No (unclear/no elaboration)" (10%). (See Table 14).

Categories	**Meaning unit(s) examples**
Question 1a	
Scientific (no elaboration or non-sequitur)	"Yes because animals insides might relate to it." – Student 7P
All investigation are scientific	"I think any investigation is scientific…" – Student 7Q
No, requires intervention	"No, because he wasn't testing anything…" – Student 7DD
It was scientific, involves data collection	"I think this experiment is scientific because he collected data from different types of birds and got enough info to conclude his investigation fairly." – Student 7V
It was scientific, involves problem-solving	"[Yes, because] he is collecting data and solving problems…" – Student 7W
Question 1b	
Yes (unclear/no elaboration)	"This was an experiment because there were lots of possible outcomes…" – Student 7V
No (unclear/no elaboration)	"No because it can either be related or not and cannot have loads of different outcomes." – Student 7I
Not an experiment, no intervention	"No, because he wasn't testing anything." – Student 7K
It was an experiment, involves observation	"I think it is an experiment because you are examining what birds eat and what type of bird it is." – Student 7CC "The reason why I think it's a scientific experiment is because hes looking at different types of birds and what they eat." – Student 7A
It was an experiment, involves data collection	"… he is collecting data … like why birds have different shaped beaks and that is what people do in investigations…" – Student 7W
It was an experiment, involves problem-solving	"… he is … problem-solving like why birds have different shaped beaks and that is what people do in investigations …" – Student 7W
Question 1c	
Yes (unclear/no elaboration)	"Yes because a investigation dont need to watching bird and see what nut they eat it could be the shape of a rock … [unclear] … effect the way it travel." – Student 7CC
No significant examples given	[absence of examples as required by question (see Table 4)]
No, an investigation follows one method	"Investigations cannot fairly/correctly follow more than one method…" – Student 7V
Yes, an investigation can follow different methods: different accuracy	"I think a scientific investigation can follow more than one method because you would have more accurat data if you try different and new ways to do things." – Student 7Y "… there are different ways to do them but each one will be more or less effective than the next" – Student 7I
Yes, an investigation can follow different methods: types of measurement	"Yes because there are lots of ways to do something scientifically" – Student 7DD "I would conclude that the investigation can follow more than one method … [e.g.] seeing how they compare to an object that you know height of; or they could simply use a tape measure" – Student 7F

Table 14: Examples of coding categories and associated meaning units for VASI questionnaire, question 1

For question 1c, 24% of responses were categorised as “No, an investigation follows one method”, 29% as “Yes, an investigation can follow different methods: types of measurement”, and 12% as “Yes, an investigation can follow different methods: different accuracy” (accuracy, here, is not taken as the strictly scientific use of the word, and may, for example, encompass “effective”, or similar; it is, however, considered to be related to scientific accuracy). Other categories include: “Yes (unclear/no elaboration)” (24%) and “No significant examples given” (24%). (See Table 14).

79% of responses to question 2 were categorised as “Rudimentary”, 63% as “Yes, gives purpose/direction to the investigation”, and 11% as “No, can start with a non-scientific question (undefined)”. Other categories include: “Yes (unclear/no justification)” (16%). Table 15 provides examples of coding categories and associated meaning units for this question.

Categories	**Meaning unit(s) examples**
Yes (unclear/no justification)	“Yes Because siance [science] cannot solve everything but some times is can solve Lots of things.” – Student 7D
Yes, gives purpose/direction to the investigation	“I think yes because if there is no scientific question there is no point doing the experiment” – Student 7L “I agree with the student who said yes because technically you can’t solve anything without a problem because there would be nothing to solve…” – Student 7W
No, can start with a non-scientific question (undefined)	“It could be any question to start with a scientific investigation, so I’m going with no.” – Student 7Q

Table 15: Examples of coding categories and associated meaning units for VASI questionnaire, question 2

Table 16 provides examples of coding categories and associated meaning units for questions 3a and 3b. For question 3a, for those responses with meaning units that were interpreted as agreeing with the claim that scientists will arrive at the same conclusion, the categories generated were as follows: “Yes, same question, same answer and therefore same conclusion” (25%), and “Unless there is a mistake, it is the same” (10%). For those responses with meaning units that were interpreted as disagreeing with the claim, the categories generated were as follows: “Scientist might collect different data” (50%), and “Scientists might have different opinions” (20%).

56% of responses to question 3b were categorised as “Rudimentary”, and 11% demonstrated some engagement with SPE. For those responses with meaning units that were interpreted as agreeing with the claim that scientists will arrive at the same conclusion, the categories generated were as follows: “Yes, same question, same answer and therefore same conclusion” (22%), and “Unless there is a mistake, it is the same" (23%). For those responses with meaning units that were interpreted as disagreeing with the claim, the categories generated were as follows: "Scientists might collect different data" (28%), "Scientists might have different opinions" (11%), and "Different procedures, different outcomes" (17%). Other categories include: "Yes (unclear/no justification)" (6%).

Categories	**Meaning unit(s) examples**
Question 3a	
Yes, same question, same answer and therefore same conclusion	"Yes, if they are all clever/smart" – Student 7I "If several scientists ask the same question and do the same procedure they will get the same answer…" – Student 7H
Scientists might collect different data	"No because people will get different results" – Student 7CC
Scientists might have different opinions	"I believe that the two [scientists] will not necessarily find the same conclusion as the personal belief that something is what causes something else [might be different]." – Student 7N
Unless there is a mistake, it is the same	"no. because someone might do something a little bit wrong." – Student 7L
Question 3b	
Yes, same question, same answer and therefore same conclusion	"No, because someone might do a procedure that doesn't work so they might get a different answer." – Student 7L "No because one of the methods might not be as accurate." – Student 7K [Both of these imply that a single answer exists and is obtainable contingent on a 'correct' procedure being used.]
Scientists might collect different data	"…you will probably get a different answer each time but there is a chance you get the same answer." – Student 7CC "No because all the vareables are different." – Student 7DD
Scientists might have different opinions	"Not necessarily because everyone is different therefore they may well come up with different answers if there's a different solution." – Student 7C
Unless there is a mistake, it is the same	"no, because someone might do a procedure that doesn't work so they might get a different answer." – Student 7L
Different procedures, different outcomes	"They will not because they do different strategies." – Student 7E

Table 16: Examples of coding categories and associated meaning units for VASI questionnaire, question 3

Basic and Extended profiles for VASI question 1a

Table 17 shows the categories used to construct an extended profile for VASI question 1a. Criteria i and ii (see *Basic and Extended meta-categories*, above) contribute significantly to the construction of Basic and Extended profiles.

Basic	Extended
Scientific (no elaboration or non-sequitur) All investigations are scientific No, requires intervention	It was scientific, involves data collection It was scientific, involves problem-solving
Percentage of Basic and Extended profiles	
79%	21%

Table 17: VASI questionnaire, question 1a, Basic and Extended categories

Basic and Extended profiles for VASI question 1b

Table18 shows the categories used to construct an extended profile for VASI question 1a. Criteria i and ii both contribute significantly to the construction of Basic and Extended profiles.

Basic	Extended
Yes (unclear/no elaboration) No (unclear/no elaboration)	It was an experiment, involves data-collection It was an experiment, involves observation It was an experiment, involves observation as a means to discover Not an experiment, no intervention" *providing participant's profile was Extended for question 1a*
Percentage of Basic and Extended profiles	
55%	45%

Table 18: VASI questionnaire, question 1b, Basic and Extended categories

Basic and Extended profiles for VASI question 1c

Table 19 shows the categories used to construct an extended profile for VASI question 1a. Criteria i and ii both contribute significantly to the construction of Basic and Extended profiles.

Basic	Extended
No, an investigation follows one method Yes (unclear/no elaboration)	Yes, an investigation can follow different methods: types of measurement Yes, an investigation can follow different methods: different accuracy
Percentage of Basic and Extended profiles	
59%	41%

Table 19: VASI questionnaire, question 1c, Basic and Extended categories

Basic and Extended profiles for VASI question 2

Table 20 shows the categories used to construct an extended profile for VASI question 1a. Criteria i and ii both contribute significantly to the construction of Basic and Extended profiles.

Basic	**Extended**
No, can start with a non-scientific question (undefined) Yes (unclear/no justification)	Yes, gives purpose/direction to an investigation
Percentage of Basic and Extended profiles	
37%	63%

Table 20: VASI questionnaire, question 2, Basic and Extended categories

Basic and Extended profiles for VASI question 3a

Table 21 shows the categories used to construct an extended profile for VASI question 1a. Criteria i and ii both contribute significantly to the construction of Basic and Extended profiles.

Question 3a	
Basic	**Extended**
Yes, same question, same answer and therefore same conclusion Unless there is a mistake, it is the same	Might collect different data Scientists might have different opinions
Percentage of Basic and Extended profiles	
55%	45%

Table 21: VASI questionnaire, question 3a, Basic and Extended categories

Basic and Extended profiles for VASI question 3b

Table 22 shows the categories used to construct an extended profile for VASI question 1a. Criteria i and ii both contribute significantly to the construction of Basic and Extended profiles.

Question 3b	
Basic	**Extended**
Yes, same question, same answer and therefore same conclusion Unless there is a mistake, it is the same	Might collect different data Scientists might have different opinions Different procedures, different outcomes
Percentage of Basic and Extended profiles	
56%	44%

Table 22: VASI questionnaire, question 3a, Basic and Extended categories

Discussion

The overarching research question for this study is: "What are the scientific personal epistemologies of students aged 11-12 (Year 7)?". Three research questions were formulated to address this overarching research question; they were:

RQ 1: How do students cluster knowledge?

RQ 2: Do students appeal to science to address questions that have traditionally been addressed by both scientific and non-scientific disciplines?

RQ 3: How do students articulate their scientific personal epistemologies?

Each research question is addressed, in turn, in respect of the results of this study.

RQ 1: How do students cluster knowledge?

The results of the study – in particular the *Person A knows…* instrument – suggest that there is a lack of uniformity for students aged 11-12 in clustering knowledge according to discipline; there is a fairly even spread in terms of the proportion of responses to which students offer a discipline-consistent response (see Figure 6). Previous research suggests that students of a similar age to those in the present study tend to cluster knowledge according to discipline, although they do not do this invariably (Danovitch & Keil, 2004); that is, the students' discipline-consistent knowledge clustering is not as 'well-formed' compared to the findings of previous research (Danovitch & Keil, 2004).

The potential to have a conception of the discipline of science – and, therefore, a SPE – is contingent on the ability to cluster knowledge in a discipline-consistent fashion. The irregularity with which students cluster knowledge according to discipline might suggest an inchoate and nebulous concept of a 'domain of science', and therefore a similarly inchoate and nebulous SPE; it may be a SPE characterised by instability (see Yang and Tsai (2010) for a further discussion on unstable personal epistemologies). Considering the importance of domain-specificity in personal epistemology (e.g. Sandoval, 2005; Feucht, 2010), the inability to formulate a domain of science has implications for, *inter alia*, how students identify sources of knowledge and how they conceive the structure of knowledge. The results suggest students may only irregularly favour traditional authorities in science, and only irregularly, appeal to science as a source of knowledge.

RQ 2: Do students appeal to science to address questions that have traditionally been addressed by both scientific and non-scientific disciplines?

If students can cluster knowledge in a discipline-consistent fashion, even if not routinely, it is necessary to establish if students favour science as a means of addressing particular questions. This is fundamental to the differentiation of a discipline, since its value stems from its privileged status in addressing particular questions and in constructing knowledge claims of a particular kind.

The *Whom would you ask?* and *Healing Crystals* instruments both suggest that students appeal preferentially to science to address questions that have traditionally been addressed by both scientific and non-scientific disciplines. The origins of the universe, human origins, supernatural phenomena, and pseudoscientific alternative medicine claims are all frequently considered to be subject to scientific scrutiny.

However, in accordance with the results regarding clustering of knowledge, there is not a unanimous agreement, nor consistency for individuals. Taken together, the *Whom would you ask?* And *Person A knows…* instruments suggest that students are generally able to cluster knowledge in to disciplines when the knowledge-discipline connection is relatively straightforward – students can associate knowledge with an appropriate profession when the knowledge claim and the profession are familiar and often associated – yet students frequently exhibit difficulty in clustering knowledge in a discipline-specific way when knowledge is inferred (see Danovitch & Keil, 2004, for similar findings). This would suggest difficulties in evaluating sources of knowledge, and therefore potential issues in the processes involved in the justification of knowledge.

Further, the *Gorvald meets…* and *Whom would you ask?* instruments suggest that students' demarcation of science from non-science, at least as they articulate it, is relatively unrefined. This is captured succinctly in the meaning units relating to overlapping/non-overlapping magisteria: only approximately 5% of students provided an intimation of non-overlapping magisteria for the distinct domains of religion and science (see Gould, 1999), without any justification for what the different epistemic values or practices might be.

Students' SPEs are unlikely to be 'self-contained' – resembling little of an expected *scientific* personal epistemology and showing significant overlap with other personal epistemologies employed in other contexts. Consequently, in attempting to acquire knowledge in some particular subject (e.g. human origins), students may appeal to scientific and non-scientific disciplines and both scientific and non-scientific epistemic values and practices.

RQ 3: How do students articulate their scientific personal epistemologies?

The profiles constructed here correspond approximately to the "dualistic", "absolutist", "naïve", and similar classifications found in personal epistemology and NOS research. This is consistent with previous research, such as that of Smith (2000), Khishfe (2008), Carey et al. (1989) and Lederman et al. (2019). When students engage in a consideration of SPE, they produce, for the most part, only a 'rudimentary' description.

A survey of the Basic and Extended categories demonstrates this. The Extended profiles – those that venture beyond the 'standard' responses of the class – show the depth of engagement with NOS and SI. There was an appreciable representation of profiles in the Extended meta-category: for a number of instruments, around half of the profiles were considered Extended (e.g. *Gorvald meets a scientist, Healing Crystals*, VASI question 1b, 1c, 3a and 3b); however, comparing the categories to the NOS and SI aspects in Table 1 evinces the shallowness of this engagement, and the Extended categories still suggest only a rudimentary SPE. Most students could provide a description of 'school science' (biology, physics and chemistry), and approximately half the students intimated an understanding of science as a means to understand and explain phenomena in, to put it crudely, the "what" and "how" sense. The majority of students recognised the importance of questions in scientific investigations, and approximately 1 in 5 students emphasised experimentation.

There is, however, occasional indications of (relatively) more 'sophisticated' profiles from the Extended categories. Science emerges from the values and practices of a community; it is, fundamentally, a human endeavour (e.g. Merton, 1973). Students seem to recognise a 'human element' to science. Approximately half of the students believe that, whether the same or a different procedure is used, different data can emerge. Some students appear to conceive of science as a 'human construct', and as having a subjective component: approximately one in five students believed that the opinions of scientists can influence the conclusions of a scientific investigation, even when the same procedure is used.

Some students 'extend' scientific practice to include "observation" – an important practice in, for example, astronomy and evolutionary biology; most students considered the scenario from VASI question 1 (see Table 3) to be scientific (despite it not being an archetypal experiment), and 20% considered it to be scientific, despite not considering it an experiment at all. "Discovery" as a characteristic of science also makes a fleeting appearance; this may be insignificant – caution has to be applied when making signifier-signified connections – but discovery is a cornerstone of science (e.g. Wootton, 2015), and students may be attempting to articulate this intuition.

Even if some students were to articulate a conception of science in a way more akin to a "sophisticated", "evaluativist" or "informed" frame, this is perhaps not sufficient without at least a basic warrant for such a position. A student may experience experimentation in the classroom, but this does not mean students understand *why* experiment is practised by the scientific community; consequently, students may exhibit what Carey et al. (1989) refer to as a copy theory of knowledge. This conclusion is consistent with the findings of Lederman et al. (2019).

Indeed, these 'extended' utterances tend to be ill-defined and without meaningful justification or elaboration. For example, as mentioned, approximately 20% of students frequently emphasise "experiment", but it is difficult to discern from the data what students considered to be experiment. More than half of the students considered the scenario from VASI question 1 to be an experiment. In most cases, it is not clear why; for others, because it entailed "data collection" and "problem solving". For some students, experiment seems to require an intervention; for others, observation is sufficient. It is not clear what students conceive experiment or scientific practice 'to be'; or, crucially why experimentation might be important in science; or why experimentation might provide criteria for demarcation. Question 2 of the *Healing Crystals* instrument, which attempted to engage students with a deeper consideration of what constitutes "scientific" evidence, produced a large number of tautological responses. Again, this is consistent with a copy theory: students might state that evidence should be 'scientific', or reasoning should be 'scientific', but do not have a robust conception (or, at least, cannot articulate a conception) of what this means: therefore, scientific evidence is evidence that is scientific.

The scientific personal epistemologies of students aged 11-12

What are the scientific personal epistemologies of students aged 11-12? Although the results demonstrate some variation amongst the students, a 'generic', representative SPE can be extracted from the data.

This study suggests that students have a nebulous and unstable conception of the domain of science, and in accordance with this, a rudimentary and inconsistent SPE. There is likely a causal relationship. Consider the context-dependency in personal epistemology: without a conception of a well-demarcated domain of science, it would be difficult to invoke in the appropriate context a personal epistemology that is scientific; further, without a reasonable understanding of NOS and SI, it would be difficult for students to begin to differentiate science from non-science, and therefore to construct a well-demarcated domain of science.

It would be informative to:

i) Test the validity of the instruments used here. In particular, although adapted from, or developed with reference to, existing instruments, it is important to acknowledge that the process of adaptation may alter their validity, and this would require testing.
ii) Extend this study to gain a better insight in students' SPE. Case-studies lend themselves to mixed-methods approaches, which can offer triangulation and superior data for analysis (Denscombe, 2017, p.66, and chapter 11).
iii) Investigate the SPEs of students at the end of their secondary education. This would help to determine how science education in the UK may be contributing to the development of students' SPE, and the 'trajectory' of this development.

Implications

Science education is, fundamentally, about training students to 'be' scientists; this should equip students with the knowledge, practices and values to pursue careers in science, to be scientifically-literate citizens, and to effectively exercise similar skills in the social and political domain. Further, there may be a positive causal relationship between SPE and science learning (e.g. Hammer & Elby, 2003; Lising & Elby, 2005; Lederman, 2007; Rule & Bendixen, 2010), and metacognition and 'epistemic volition' regarding personal epistemology and NOS may facilitate science learning (e.g. Hofer, 2004; Rule & Bendixen, 2010). As such, it is important for science teaching and learning to be sensitive to the effective development of students' SPEs.

The present study suggests that students entering secondary school lack a robust and sophisticated SPE, with negative implications for the value a SPE may have for those factors presented above. The implications from this study are, at the very least, that educators should be sensitive to students' rudimentary understanding of the epistemic values and practices of science, that students have the capacity to hold more sophisticated epistemologies after appropriate intervention (e.g. Carey et al., 1989; Khsihfe, 2008; Lehrer, Schauble & Lucas, 2008), and that lessons should be designed to encourage explicit engagement with personal epistemology, the nature of science, and scientific inquiry. Utilising the history, philosophy and sociology of science would seem a promising method (e.g. Abd-El-Khalick & Lederman, 2000; McComas, 2008; Fouad, Masters & Akerson, 2015).

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, 37(10), 1057-1095.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education*, 95(3), 518-542.

Allchin, D. (2012). Toward clarity on whole science and KNOWS. *Science Education*, 96(4), 693-700.

Ben-Ari, M. (2005) *Just a theory: exploring the nature of science*. Prometheus Books, Amherst, N.Y.

Biagioli, M. (1993). *Galileo, courtier: The practice of science in the culture of absolutism*. University of Chicago Press.

Bricker, L. A., & Bell, P. (2016). Exploring images of epistemic cognition across contexts and over time. In J. A. Greene, W. A. Sandoval, & I. Bråten (Eds.), *Handbook of epistemic cognition* (pp.375-392). New York, NY: Routledge.

British Educational Research Association (BERA), (2011). Ethical guidelines for educational research. Retrieved from: https://www.bera.ac.uk/wp-content/uploads/2014/02/BERAEthical-Guidelines-2011.pdf

Bromme, R., Kienhaus, D. & Porsch, T. (2010) Who knows what and who can we believe? Epistemological belief are beliefs about knowledge (mostly) to be attained from others. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal epistemology in the classroom: Theory, Research, and Implications for Practice* (pp.163-193). Cambridge: Cambridge University Press.

Buffler, A., Lubben, F., & Ibrahim, B. (2009). The relationship between students' views of the nature of science and their views of the nature of scientific measurement. *International Journal of Science Education*, 31(9), 1137-1156.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). "An experiment is when you try it and see if it works": A study of grade 7 students' understanding of the construction of scientific knowledge. *International Journal of Science Education*, 11, 514–529.

Cavagnetto, A. R. (2010). Argument to foster scientific literacy: A review of argument interventions in K–12 science contexts. *Review of Educational Research*, 80(3), 336-371.

Chandler, M. J. & Proulx, T. (2010) Stalking young persons' changing beliefs about belief. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal epistemology in the classroom: Theory, Research, and Implications for Practice* (pp.197-219). Cambridge: Cambridge University Press.

Chin, C., & Teou, L. Y. (2009). Using concept cartoons in formative assessment: Scaffolding students' argumentation. *International Journal of Science Education*, 31(10), 1307-1332.

Clough, M. P. (2008). Teaching the nature of science to secondary and post-secondary students: questions rather than tenets. *California Journal of Science Education*, 8(2), 31–40.

Cohen, L., Manion, L. & Morrison, K. (2011). *Research Methods in Education* (7^{th} Ed.). Oxon: Routledge.

Conley, A. M., Pintrich, P. R., Vekiri, I., & Harrison, D. (2004). Changes in epistemological beliefs in elementary science students. *Contemporary educational psychology*, 29(2), 186-204.

Dale, R., Dietrich, E., & Chemero, A. (2009). Explanatory pluralism in cognitive science. *Cognitive Science*, 33(5), 739-742.

Danovitch, J. H., & Keil, F. C. (2004). Should you ask a fisherman or a biologist?: Developmental shifts in ways of clustering knowledge. *Child Development*, 75(3), 918-931.

Deng, F., Chen, D. T., Tsai, C. C., & Chai, C. S. (2011). Students' views of the nature of science: A critical review of research. *Science Education*, 95(6), 961-999.

Denscombe, M. (2017). *The good research guide: For small-scale social research projects* (6th ed.). London: Open University Press.

Drost, E. A. (2011). Validity and reliability in social science research. *Education Research and perspectives*, 38(1), 105.

Eagleton, T. (2008) *Literary theory: An introduction*. Minneapolis: University of Minnesota Press.

Elby, A. (2009) Defining Personal Epistemology: A Response to Hofer & Pintrich (1997) and Sandoval (2005), *Journal of the Learning Sciences*, 18(1), 138-149.

Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of advanced nursing*, 62(1), 107-115.

Feucht, F. (2010) Epistemic climate in elementary classrooms. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal epistemology in the classroom: Theory, Research, and Implications for Practice* (pp.55-93). Cambridge: Cambridge University Press.

Feucht, F. (2017). The Epistemic Beliefs of Fourth Graders about the Verification of Second-Hand Knowledge and Its Knowledge Sources. *Journal of Education and Human Development*, 6(1), 7-26.

Forman, J., & Damschroder, L. (2008). Qualitative content analysis. In L. Jacoby & L. Siminoff (Eds.), *Empirical methods for bioethics: A primer* (Advances in bioethics) (pp.39-62). Oxford: Elsevier.

Fouad, K. E., Masters, H., & Akerson, V. L. (2015). Using history of science to teach nature of science to elementary students. *Science & Education*, 24(9-10), 1103-1140.

Godfrey-Smith, P. (2003) *Theory and reality: an introduction to the philosophy of science*. Chicago: University of Chicago Press.

Gould, S. J. (1999) Rocks of Ages: Science and Religion in the Fullness of Life. London: Vintage.

Greene, J. A., Azevedo, R., & Torney-Purta, J. (2008). Modeling epistemic and ontological cognition: Philosophical perspectives and methodological directions. *Educational Psychologist*, 43(3), 142-160.

Greene, J. A., Torney-Purta, J., Azevedo, R., & Robertson, J. (2010). Using cognitive interviews to explore elementary and secondary school students' epistemic cognition. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal epistemology in the classroom: Theory, Research, and Implications for Practice* (pp.368-405). Cambridge: Cambridge University Press.

Greeno, J. G. (2015). Commentary: Some prospects for connecting concepts and methods of individual cognition and of situativity. *Educational psychologist*, 50(3), 248-251.

Halpenny, A. M., & Pettersen, J. (2013). *Introducing Piaget: A guide for practitioners and students in early years education*. London: Routledge.

Hammer, D. & Elby, A. (2003) Tapping Epistemological Resources for Learning Physics. *The Journal of the Learning Sciences*, 12(1), 53-90.

Hammer, D., & Elby, A. (2002). On the form of a personal epistemology. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: The psychology of beliefs about knowledge and knowing* (pp.169-190). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Harrison, G. M., Duncan Seraphin, K., Philippoff, J., Vallin, L. M., & Brandon, P. R. (2015). Comparing models of nature of science dimensionality based on the next generation science standards. *International Journal of Science Education*, 37(8), 1321-1342.

Hofer, B. K. (2004). Epistemological understanding as a metacognitive process: Thinking aloud during online searching. *Educational Psychologist*, 39(1), 43-55.

Hofer, B., & Pintrich, P. (1997). The Development of Epistemological Theories: Beliefs about Knowledge and Knowing and Their Relation to Learning. *Review of Educational Research*, 67(1), 88-140.

Hofmann, W., Gawronski, B., Gschwendner, T., Le, H., & Schmitt, M. (2005). A meta-analysis on the correlation between the Implicit Association Test and explicit self-report measures. *Personality and Social Psychology Bulletin*, 31(10), 1369-1385.

Kampourakis, K. (2016). The “general aspects” conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching*, 53(5), 667-682.

Keogh, B., & Naylor, S. (1999). Concept cartoons, teaching and learning in science: an evaluation. *International Journal of Science Education*, 21(4), 431-446.

Khishfe, R. (2008). The development of seventh graders' views of nature of science. *Journal of Research in Science Teaching*, 45(4), 470-496.

King, P. & Kitchener, K. (1994) *Developing reflective judgement: Understanding and promoting intellectual growth and critical thinking in adolescents and adults*. San Francisco: Jossey-Bass.

Kuhn, D. & Weinstock, M. (2002) What is epistemological thinking and why does it matter? In B. K. Hofer and P. R. Pintrich (Eds.), *Personal epistemology: The psychology of belief about knowledge and knowing* (pp.121-144). Mahwah, NJ: Lawrence Erlbaum Associates.

Kuhn, D. (1999). A developmental model of critical thinking. *Educational researcher*, 28(2), 16-46.

Kuhn, T. S. (2012). *The structure of scientific revolutions*. University of Chicago press. (Original work published 1962).

Leblebicioglu, G., Metin, D., Capkinoglu, E., Cetin, P. S., Dogan, E. E., & Schwartz, R. (2017). Changes in students’ views about nature of scientific inquiry at a science camp. *Science & Education*, 26(7-9), 889-917.

Lederman, J., Lederman, N., Bartels, S., Jimenez, J., Akubo, M., Aly, S., et al. (2019). An international collaborative investigation of beginning seventh grade students' understandings of scientific inquiry: Establishing a baseline. *Journal of Research in Science Teaching*, 56(4), 486-515.

Lederman, J., Lederman, N., Bartos, S., Bartels, S., Meyer, A. & Schwartz, R. (2014) Meaningful Assessment of Learners’ Understandings About Scientific Inquiry – The Views About Scientific Inquiry (VASI) Questionnaire. *Journal of Research in Science Teaching*, 51(1), 65-83.

Lederman, N. G. (1986). Students' and teachers' understanding of the nature of science: A reassessment. *School Science and Mathematics*, 86(2), 91-99.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell, & N. G. Lederman (Eds.), *Handbook of research on science education* (pp.831–879). Mahwah, NJ: Erlbaum.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of research in science teaching*, 39(6), 497-521.

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In Abell, & N. G. Lederman (Ed.), *Handbook of research on science education* (volume II; pp.600–620). New York, NY: Routledge.

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. *Cognitive development*, 23(4), 512-529.

Lising, L., & Elby, A. (2005). The impact of epistemology on learning: A case study from introductory physics. *American Journal of Physics*, 73(4), 372-382.

Lutz, D. J., & Keil, F. C. (2002). Early understanding of the division of cognitive labor. *Child development*, 73(4), 1073-1084.

Mason, L. (2016) Psychological Perspectives on Measuring Epistemic Cognition. In J. A. Greene, W. A. Sandoval, & I. Bråten (Eds.), *Handbook of epistemic cognition* (pp.375-392). New York, NY: Routledge.

Matthews, M. R. (2012). Changing the focus: from nature of science (NOS) to features of science (FOS). In M. Khine (Ed.), *Advances in Nature of Science Research* (pp.3–26). Dordrecht: Springer.

McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education*, 17(2-3), 249-263.

Merton, R. K. (1973). *The sociology of science: Theoretical and empirical investigations*. University of Chicago press: Chicago.

Mitchell, S. D. (2003). *Biological complexity and integrative pluralism*. Cambridge: Cambridge University Press.

Naylor, S., Keogh, B., & Downing, B. (2007). Argumentation and primary science. *Research in science education*, 37(1), 17-39.

Perry, W. (1970). *Forms of intellectual and ethical development in the college years; a scheme.* New York: Holt, Rinehart and Winston.

Popper, K. (2002) *The Logic of Scientific Discovery*. London: Routledge. (Original work published 1959).

Popper, K. (2012) *The Open Society and Its Enemies.* London: Routledge Classics. (Original work published 1945).

Rudolph, J. D. (2000). Reconsidering the "nature of science" as a curriculum component. *Journal of Curriculum Studies,* 32(3), 403–419.

Rule, L. & Bendixen, D. (2010) The integrative model of personal epistemology development: theoretical underpinnings and implications for education. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal epistemology in the classroom: Theory, Research, and Implications for Practice* (pp.95-123). Cambridge: Cambridge University Press.

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. *Science Education*, 89(4), 634-656.

Sandoval, W. A. (2009). In defence of clarity in the study of personal epistemology. *The Journal of the Learning Sciences*, 18(1), 150-161.

Sandoval, W. A., Greene, J. A., & Bråten, I. (2016). Understanding and Promoting Thinking About Knowledge: Origins, Issues, and Future Directions of Research on Epistemic Cognition. *Review of Research in Education*, 40(1), 457–496.

Schommer, M. (1990). The effects of beliefs about the nature of knowledge in comprehension. *Journal of Educational Psychology*, 82(3), 498–504.

Schommer, M. (1994). Synthesizing epistemological belief research: Tentative understandings and provocative confusions. *Educational psychology review*, 6(4), 293-319.

Schommer-Aikins, M. (2004). Explaining the epistemological belief system: Introducing the embedded systemic model and coordinated research approach. *Educational psychologist*, 39(1), 19-29.

Shapin, S., & Schaffer, S. (2011). *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life.* Princeton: Princeton University Press.

Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experiences on epistemological development. *Cognition and Instruction*, 18(3), 349-422.

Suzuri-Hernandez, L. J. (2010). *Exploring school students' views of the nature of science* (Doctoral dissertation, University of York).

Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *American journal of evaluation*, 27(2), 237-246.

Wootton, D. (2015). *The invention of science: A new history of the scientific revolution*. UK: Penguin Random House.

Yang, F.-Y. & Tsai, C.-C. (2010) An epistemic framework for scientific reasoning in informal contexts. In L. D. Bendixen & F. C. Feucht (Eds.), *Personal epistemology in the classroom: Theory, Research, and Implications for Practice* (pp.197-219). Cambridge: Cambridge University Press.