Practical work in science: misunderstood and badly used?

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ABSTRACT This article argues that the role of practical work in science is overemphasised and misunderstood. Science is distinguished by the fact that it is a set of ideas about the material world and not by empirical enquiry. The latter is only one of six styles of reasoning that have been used to develop scientific ideas. The lack of clarity around the role of practical work in science means that it is often poorly used in the teaching and learning of science. And, until its role is clarified, attempts to assess it are of little value.

In this article, I seek to argue that the current clamour for the value of practical work in school science is misconceived and places too much emphasis on just one of the many activities necessary to do and understand science. This is not to say that practical work does not have a role, which I will elaborate, but that that role is both limited and misunderstood. As a consequence, the research evidence suggests that practical work is used badly and ineffectively. This matters, as school science in the UK is overwhelmingly taught in laboratories – laboratories that are both expensive to build and expensive to maintain. Indeed, the provision in the UK is better than most other countries. Justifying such expenditure demands that the field of science education is clear about the role and value of practical work – a clarity that I will argue is absent to date, with one or two notable exceptions.

My argument begins with the point that science is fundamentally about *ideas*. Experiments serve merely to test the many ideas that are the product of the creative imagination of scientists. As such, experiments are handmaidens to the greater project of developing those ideas rather than the primary goal of science itself. Even then, experimental exploration is only one of six major forms of reasoning that science has contributed to our culture. I then turn to the evidence which shows that practical ability is dependent on a body of procedural knowledge (a body of knowledge that is poorly defined in most curricula), to argue that developing such knowledge should be the primary goal of laboratory work rather than a set of nebulous and ill-defined practical 'skills'. That then leads me to ask what are other valid arguments for practical work. Two reasons stand out. First, it offers an opportunity for students to experience phenomena themselves – an experience for which there is no substitute. Second, when undertaken appropriately, it offers students the opportunity to experience the activity of enquiry – although this is predominantly limited to the testing of scientific ideas and reflects only a limited set of the kinds of empirical enquiry that scientists do undertake.

Science is about ideas

To begin, the defining feature of science is that it is a set of ideas about the material and living world. And, although experimentation is an important feature of science, it is not *the* defining feature. Moreover, these ideas do not readily emerge from observation and experiment. Everyday experience, for instance, tells you that day and night is caused by a moving Sun; science tells you that it is caused by a moving Earth. Everyday experience tells you that objects in motion normally slow down; Newton's first law attempts to tell you that things keep on going forever at constant velocity. Everyday experience leads you to the idea that the matter in a plant comes from the ground; science tells you it mostly comes from the air; and so on. As the British philosopher Michael Oakeshott (1933: 171) wrote:

in science it is found necessary to leave behind the world of perception; for so long as we are bound to this world what we are seeking must elude us. Scientific knowledge is not 'organized, common *sense'; it is a world which begins to exist only when common sense and all of its postulates have been forgotten or rejected.*

Perhaps most tellingly, he points out that science '*begins neither with the "collection of data", nor with measurement, neither with experiment nor with observation, but with a* world of scientific ideas [emphasis added]' (p.182). One simple way of illustrating the importance of ideas, or what might more accurately be called theories, is to ask any group to think of the names of some famous scientists. The names that emerge are dominated by those who made important theoretical contributions to science, such as Darwin, Einstein, Maxwell, Bohr, Mendel and Hawking. Thus, as a scientist, your name is more likely to be preserved for posterity if you contribute a new idea to our understanding of the world.

The model of science offered in the USA by the *Framework for K-12 Science Education* (National Research Council, 2012) does recognise the distinctive role of ideas and their relationship to experiment by the diagram shown in Figure 1.

On the left, scientists are working in the investigational space, designing experiments and collecting, analysing and interpreting data. On the right, they are engaged in theorising about the world, developing hypotheses and constructing explanations – a feature that is undervalued in the teaching of science. In the middle, at their intersection, they are engaged in argument about their data, contrasting their data with their theoretical predictions, and identifying flaws in both their own and others' ideas – experiences that are even less common in the teaching of science.

And, given that ideas are '*the crown of science*' (Harré, 1984), it behoves the teacher of science to be clear about which idea any laboratory work is about. Indeed, the teaching of science would perhaps be better understood if we recognised that we are teachers of crazy ideas – the ideas, for instance, that we live at a bottom of a sea of air, that you look like your parents because every cell carries a chemically coded message about how to reproduce each one of us, or that most of the atom is empty space. Only when we realise this will the real role of practical work as a rhetorical artefact to provide evidence for the canonical scientific worldview become clearer.

Moreover, cognitive historians of science have shown that the ideas of science are founded on six types or styles of reasoning (Crombie, 1994; Netz, 1999). These are:

1 the use of mathematics to represent the world and for deductive argument (*mathematical deduction*);
2 the use of experimental investigation to establish patterns, to differentiate one form of object from another and to test the predictions of hypothetical models (*experimental exploration*);
3 the construction of analogical and hypothetical models to represent the world (*hypothetical modelling*);

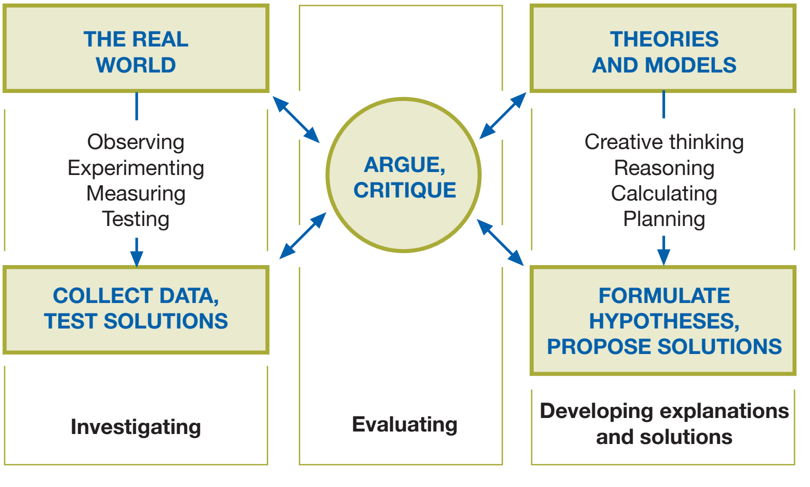

Figure 1 A model of science showing the three major spheres of activity and their constituent practices (Osborne, 2011; National Research Council, 2012)

4 the classification and ordering of variety by comparison and taxonomy (*categorisation*);
5 the statistical analysis of regularities in populations, the identification of patterns and the calculus of their probability (*probabilistic thinking*);
6 the historical accounts of the derivation of the development of species, the Earth, the solar system, the universe, the elements and more (*historical-based evolutionary thinking*).

These styles of reasoning have no necessary foundation; rather, they are simply an emergent feature of the social and cultural context where they were first developed. They exist because they have been successful in answering the three essential questions that science asks: what exists, how does it happen and how do we know. Each of these forms of reasoning brings into being a set of entities that are required to perform the reasoning. At one level, these are things such as atoms, cells, elements, vacuums, light waves, organs, species, planets, genes and dihybrid crosses or concepts such as heat, temperature, speed, displacement, adaptation and chemical equilibria. Each form of reasoning also develops procedures and entities that are needed for investigation, such as the notion of a variable and the need to control variables in experimental exploration, statistical tests for probabilistic thinking and criteria for categorising rocks, species, etc. in taxonomy. Each of these modes of thought is associated with a legendary 'hero' – Euclid and Pythagoras with Greek mathematics, Galileo with the introduction of experiment, Darwin with evolution, Linnaeus with classification, Maxwell and Einstein with mathematical modelling. Notably, however, experimental exploration *is just one mode* of reasoning. Offering a coherent account of science should require exploration of each of these styles of reasoning, and science should not be dominated by just the one – experimental exploration.

Building ideas in science

If science is a set of ideas, albeit crazy ideas, then the role of the teacher of science is to build students' understanding of the ideas and the reasoning that has led to their establishment. Ideas, as Oakeshott (1933) would argue, belong to the world of 'communicable experience'. They are only taken up to the extent that they are communicated successfully. Communicating ideas requires teachers and students to engage in five fundamental forms of experience, one of which is indeed experimental exploration (the doing of science), but, and this is a very big but, developing an understanding of an idea requires talking about it, writing about it, reading about it and representing/drawing or visualising it (Figure 2).

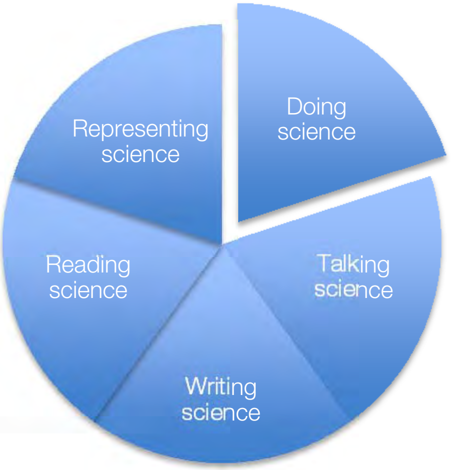

Figure 2 The pedagogic practices required for the teaching of science; adapted from Pearson, Moje, and Greenleaf (2010)

While doing science undoubtedly requires 'hands-on' experience, the other four practices require providing students with opportunities to engage in a set of literate activities that help to build an understanding of the ideas that are used to explain the phenomenon itself. Reading, talking and writing are not simply tools for storage and transmission. Rather, as Norris and Phillips (2003: 226) argue:

The relationship [between science and literacy] *is a constitutive one, wherein reading and writing are constitutive parts of science. Constitutive relationships define necessities because the constituents are essential elements of the whole. Remove a constituent, and the whole goes with it.*

Evidence to support this view is to be found in the work of Tenopir and her colleagues, which identifies that scientists and engineers devote over 50% of their time to reading and writing (Tenopir and King, 2004). Similar arguments are elegantly expressed by Postman and Weingarter (1971: 85), who argue:

Almost all of what we customarily call 'knowledge' is language, which means that the *key to understanding a subject is to* understand its language [emphasis added] … *This means, of course, that every teacher is a language teacher: teachers, quite literally, have little else to teach, but a way of talking and therefore seeing the world.*

Moreover, if these literate practices were given anywhere near the same amount of time and space as is devoted to empirical work, research evidence suggests that science teaching would become much more successful. Chi (2009), for instance, shows that students who are asked to engage in the discussion of ideas perform better than students who merely produce a written product who, in turn, perform better than students who are just active.

However, time and time again, the overwhelming picture that emerges from the research on school practical work is that it requires students to be little more than active. For instance, in their work looking at the quality of discussions surrounding practical work in two year 8 (age 12–13) classrooms where they focused on four groups of students for over 200 minutes of observation, Watson, Swain and McRobbie (2004: 14) concluded that:

- much of the work was routinised;
- '*on the whole students did not justify their claims*';
- students '*did not understand the educational aims of the inquiry*';
- there was no discussion of the conceptual knowledge needed to make sense of the results;
- there was '*no attempt to seek an explanation of the results or to discuss the strength of evidence*'.

In short, a dispiriting picture of what should be a focused and productive educational activity. Likewise, a more extensive look at 25 practical lessons conducted by Abrahams and Millar (2008: 1959) led to the conclusion that:

almost all of the student discussion observed by the researcher focused on the practicalities of carrying out the task and, in particular, on who would do what with which piece of equipment and when they could swap roles.

Given that the fundamental purpose of practical work is to help students make links between the world of ideas and the real world of objects and events, there is little evidence that such work is contributing to this goal. Even more evidence of this failing to achieve what should be the primary objective of practical work comes from Abrahams and Reiss's (2012) evaluation of the national project 'Getting Practical: Improving Practical Work in Science—IPWiS', a project that was designed to improve the effectiveness of practical work in both primary and secondary schools in England. These researchers found that, while teachers were highly effective at getting students to do the practical work in a recipe-like manner, teachers consistently failed to incorporate activities that would make links between the observations and the scientific ideas that they were designed to illuminate. This, I would argue, shows an obsession with the doing of practical work, enabling students to perform the appropriate process. There is, however, a significant failure to engage students in the talking, reading and writing required to build the connection between the scientific idea and what the students are observing.

In contrast to my emphasis on the role of practical work for building ideas, the rhetoric of much of the current debate talks about the importance of 'skills'. For instance, the recent Royal Society (2014) report *A Vision for Science and Mathematics Education* is peppered with statements of the need for '*the skills and knowledge to make informed decisions*', the need for '*problem-solving and analytical skills*' and the need for '*high-level skills*'. Nowhere, however, does this document ever specify what it means by a skill or what its relationship to knowledge is. Such language is, at best, unfortunate. First, what is meant by a skill? Is it something that is acquired through practice such as riding a bike, learning a musical instrument or being able to serve well at tennis? If so, there is never going to be enough time in the school science curriculum – particularly given the research (Ericsson, Krampe and Tesch-Römer, 1993) that shows that it takes 10 000 hours to become expert at any practice (although undoubtedly proficiency can be achieved in a lot less time). And, if it is not this kind of skill, there must be a body of knowledge that is necessary for its performance. If so, would it not be better to describe the ability to undertake practical work as a 'competency' that requires a body of knowledge and skill? What knowledge is needed should then be made explicit and it is the responsibility of those working in education to define what that knowledge might be, while the skill element is what is tacit and acquired through practice. However, given the restricted time available in formal education, the development of such skills can only ever be limited. Moreover, the skills developed with the scientific instrumentation available in the standard school laboratory are not, given the significant difference in instrumentation, necessarily the same as needed in a university laboratory or the workplace. Hence, it must be asked, what kind of skills do people wish to see developed? Given the increasingly digital nature of instrumentation these days, considerably less skill is required to engage in experimentation.

This overemphasis on skills and the failure to make the links to the scientific ideas that are the focus of any investigation are a product of a culture where the role of practical work is ill defined, a rhetoric that focuses on the development of skills rather than ideas, and where teaching all of science in a laboratory conveys to students that the primary means of producing knowledge is engagement in some form of practical work. Indeed, there is absolutely no need for all science to be taught in a laboratory given that talking science, reading about science, writing science and representing scientific ideas can all be done in any classroom. Those who are currently upset by the omission of any practical examination from A-level need first, I would argue, to build a stronger and clearer conception of what is valuable about the practice they are defending as the empirical evidence to date would suggest that, as practised in many schools, they are defending the indefensible.

The knowledge and skill required for practical work

What kind of knowledge then is needed for practical work? One particular set of ideas that is essential to the doing of all practical work is encapsulated by the concept of 'procedural knowledge'. This was a concept developed by the Assessment of Performance Unit (APU) set up by the UK government in the 1980s to monitor, among other things, students' ability to perform investigations. Building on the APU findings, Gott and Murphy (1987) argued against seeing investigation or enquiry simply as a 'process skill'. Instead, they sought to define enquiry as an 'activity'. Within such an 'activity', they argued, students made use of both *conceptual* and *procedural* understanding. The latter was a knowledge and understanding of scientific procedures, or '*strategies of scientific enquiry*', such as '*holding one factor constant and varying the other*' when controlling variables (p. 13). This insight emerged from the finding that much of the variation in student performance on tasks could *not* be explained solely on the basis of the presence, or absence, of appropriate conceptual knowledge, for example the lack of a suitable model of the system being investigated. Rather, it was accounted for by '*procedural failures*'; that is, students not holding the *necessary procedural knowledge*. This finding led the APU to the conclusion that '*the major influence on performance on a task is the availability to the child of certain relevant items of knowledge*' and that '*carrying out a scientific investigation, then, is primarily a display of understanding, and not of skill*' (Gott and Murphy, 1987: 244).

As a consequence, Gott and Murphy argued for procedural knowledge to be taught explicitly, suggesting that '*we must accept the need to develop an explicit underpinning* [procedural] *knowledge structure in the same way that we have developed such a structure for conceptual elements of the curriculum*' (p. 52). As such, their insights offered a new perspective that made the scientific reasoning required for empirical enquiry knowledge-based rather than skill-based. This rationale was then developed further into a more complete framework, or 'taxonomy', for procedural knowledge to be taught in school science that Gott and his collaborators called '*concepts of evidence*' (Gott, Duggan and Roberts, 2008).

At a higher level, good scientists also need to know the epistemic justification for the procedures that they choose to use. Thus, while an important element of procedural knowledge is the concept of a variable, its different forms and the need to control variables, an expert would be able to explain why the control of variables is essential to establishing causal claims in science. Such knowledge is epistemic knowledge and it should be the goal of any coherent science education to build not only students' procedural knowledge but also their epistemic knowledge of the role of experiment in science, the function of peer review, and why field tests of drugs require double-blind experimental tests.

The arguments *for* practical work

What, then, are the unequivocal arguments for practical work and what are their implications? Essentially, there would appear to be two arguments:

1. its role in providing a first-hand demonstration of phenomena;
2. its role in providing an experience of what it means to engage in the *whole* experience of empirical enquiry.

The rhetorical task of the science teacher is to persuade his or her students of the validity of the scientific worldview. Given the unnatural and anti-commonsense nature of much of what we have to teach, this is no mean feat. First-hand experience of any phenomenon that behaves in the manner predicted by the scientific account is powerful evidence of its veracity. To be told that the acceleration due to gravity is $9.81\,\mathrm{m\,s^{-2}}$ is one thing. To undertake an experiment and measure it yourself is another and altogether more convincing. As Millar (1998: 26) argues:

In a teaching context, producing the phenomenon is also a kind of ritualised display of the power of scientific knowledge involved. The event implicitly proclaims: 'see, we (that is the scientific community as embodied in the teacher) know so much about this that we can get the event to happen, reliably and regularly, before your very eyes!'… Practical tasks carried out by the students are really 'auto-demonstrations', so they carry the even stronger implicit message that 'our understanding and consequent control of materials and events is so good that I (the teacher) don't even have to do it for you but you can do it yourself'.

Indeed, there is no substitute for such an experience. Despite the rhetoric, simulations and *YouTube* videos do not convey the authenticity of the scientific account in such a first-hand, vivid and memorable manner. This, for instance, is one of the primary arguments that advocates for dissection in schools make. However, the power of any such experience is wasted if students are not clear about what idea is being exemplified and if the experience is not related strongly to the idea. That so much practical work fails to achieve this goal can be observed by asking students what they most remember about science. Their response will often recall a practical they have experienced *but* they are then often unable to explain the concept or idea that it was designed to show.

The second reason has to be to offer students the opportunity to engage and experience the process of scientific enquiry. However, we need to be clear about this reason – this does not mean only the doing of the enquiry and the data collection part, which is just more 'hands-on'. Rather, there has to be a 'minds-on' component. Experiencing the *whole process* of scientific enquiry means that students have to understand the question they are asking, engage in the process of designing an appropriate experiment or data collection exercise, collect the data, and then analyse and interpret the data to establish what kinds of claims can be supported by the data. Only if these other components are included, and only if as much time is devoted to them as to the data collection, can the process be justified. Not surprisingly, if students are to be offered this experience, it can rarely be done in a single lesson. Indeed, the excessive time devoted to data collection is questionable given the increasing ease with which it is supported by modern technology. The average smartphone, for instance, has become a very sophisticated instrument capable of measuring light levels, sound levels, reaction times, heartbeats and acceleration and conducting real-time Fourier analysis of the frequencies of any sounds, making all kinds of data sets easy to collect.

Moreover, developing the competence to undertake enquiry requires students to engage in a range of 'five-finger exercises' that hone the knowledge and ability to undertake such a practice. One of the best illustrations of such exercises comes from the work undertaken by the ASE–King's College London Science Investigations in Schools (AKSIS) project. In their book *Developing Understanding in Scientific Enquiry* (Goldsworthy, Watson and Wood-Robinson, 2000) published for teachers, the team developed discursive activities that asked students, for instance, to consider:

- which of five possible experimental designs might be the best;
- which of a set of data interpretations might be the most appropriate;
- what made a good question for experimental investigation.

Notably, these activities can be done outside of a laboratory and require students to discuss and construct an argument for their choices. Figure 3 shows an example of such an activity, in this case focusing on experimental design. Such activities activity

6a Dissolving sugar

A teacher asked his pupils to investigate this problem:

'How does temperature affect the time taken for sugar to dissolve in water?'

The pupils were asked to describe the investigation. These are some of the things they wrote. How clearly has each pupil described the investigation?

Jemma *We have got to write down what we are going to do and then do it.*

Kirsty *We are looking to see how different temperatures affect how long it takes for the sugar to dissolve.*

Emma *We are trying to see if sugar dissolves in water.*

Laurence *We are adding sugar to hot and cold water to see how long it will take to dissolve.*

Alex *We are trying to find the best temperature for dissolving sugar in water.*

Louise *We have to put the same amount of sugar in water with different temperatures and see what happens.*

1 Order the descriptions from best to worst.

Write down the pupil's names.

Best **Worst**

2 Write down three ways in which the best description is better than the worst description.

(a) ____________________

(b) ____________________

(c) ____________________

Figure 3 An AKSIS activity designed to build procedural understanding; reproduced from Goldsworthy, Watson and Wood-Robinson (2000) are essential for building students' knowledge of the procedures of science. Just as best practice in reading consists of a process of activating prior knowledge *before* reading, an activity to monitor comprehension and engage students *during* reading, and then a *post*-reading activity to summarise and distil the main ideas, no practical work should be undertaken without a pre- and post-activity. Asking students simply to write up their results for homework does a disservice to the role of experimental work and to student learning.

The assessment of practical work

The desire to assess practical work is driven by the belief that something that is that important should be counted. As understandable as such a view is, it is only of any value if we are clear about the constructs we wish to assess. History would suggest that, with a small number of possible exceptions*, any attempt at mass assessment of practical work, particularly when it is high-stakes, will fail. The attempt to assess students' ability to engage in investigations during the 1990s – the component of the curriculum referred to as Sc1 in the English and Welsh National Curriculum – reduced investigations to an algorithmic procedure in which teachers overwhelmingly chose one of four experiments for the purposes of assessment as the outcomes of these experiments were predictable. The conclusion of an extensive review of its implementation in schools by Donnelly *et al*. (1996: 227) was that '*Sc1 was ill-founded in substance, mishandled in its implementation and deprofessionalising in its direct impact on teachers*'. Likewise, the reason that A-level awarding bodies are currently not enthusiastic about the assessment of practical work is that its assessment had become ritualised and manipulable by teachers and students to the extent that the examination lacked validity as it failed to discriminate. In short, it was psychometrically flawed and the results had little meaning. If there is to be any assessment of practical work then two choices face the science education community. One is to assess a student's ability to design appropriate experiments, identify and control the relevant variables, and analyse and interpret data – all of which can be done with a pencil and paper test or, even better, a computer simulation. The second is to insist on a portfolio of experimental investigations conducted over the course of the year that are assessed by the teacher and moderated by groups of teachers. The conclusion to be drawn from this history is that, if we are to avoid repeating the mistakes of the past, practical work is only worth assessing if we are both clear about the constructs we wish to assess and have evidence that we can devise an assessment that is a valid measure of the competence we seek to assess. Moreover, it must discriminate well between the competent and the incompetent.

Conclusion

If the views expressed in this article engender dissonance then it will have served its main function of forcing those who disagree to make a better rationale for the role of practical work. My major point about the arguments for practical work in school science is that they are based on an erroneous conception of science and that, as practised in schools, practical work is taught in a manner that fails to exploit the potential of the resource that schools are provided with for student learning. I do not dispute that practical work is engaging. However, I would contend that one of the primary reasons students think it is engaging is because it offers a change from other lessons and provides them with a measure of autonomy that is so often missing from the rest of their school life. While this may help with student engagement, it cannot be the primary reason and justification for such a resource. Indeed, the teaching of science in a laboratory leads to a kind of Faustian contract between the students and the teacher of science. 'Why', students ask, 'is the science being taught in a laboratory if the teacher does not make use of it?' Unable to give a good answer to this tacit if not explicit question, teachers often engage in a practical activity in response, when time might much better be spent on an activity that requires them to talk about, read about, write about or represent a *scientific idea*. Given the value accorded to practical work, the onus is on us firstly to mount better arguments for an activity

* Notable here were the two-week investigation conducted for Nuffield A-Level physics during the 1970s to late 1980s, which was assessed by teachers, the biology project part of Nuffield A-level biology and the current Salters'–Nuffield A-level biology. In addition, the A-level had a practical examination that required students to assemble simple apparatus, collect data and interpret the findings.

that is seen as being so central to the teaching of science, and secondly to work to ensure the improvement of pedagogic practice. It is then hoped that research in five or ten years' time will paint a much better picture of how practical work is used to support the *teaching of scientific ideas*.

References

Abrahams, I. and Millar, R. (2008) Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science. *International Journal of Science Education*, **30**(14), 1945–1969.

Abrahams, I. and Reiss, M. J. (2012) Practical work: its effectiveness in primary and secondary schools in England. *Journal of Research in Science Teaching*, **49**(8), 1035–1055.

Chi, M. (2009) Active–constructive–interactive: a conceptual framework for differentiating learning activities. *Topics in Cognitive Science*, **1**, 73–105.

Crombie, A. C. (1994) *Styles of Scientific Thinking in the European Tradition: The History of Argument and Explanation Especially in the Mathematical and Biomedical Sciences and Arts*. vol. 1. London: Duckworth.

Donnelly, J., Buchan, A., Jenkins, E., Laws, P. and Welford, G. (1996) *Investigations by Order: Policy, Curriculum and Science Teachers' Work under the Education Reform Act*. Nafferton: Studies in Science Education.

Ericsson, K. A., Krampe, R. T. and Tesch-Römer, C. (1993) The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, **100**(3), 363–406. Available at: projects.ict.usc.edu/itw/gel/EricssonDeliberatePracticePR93.pdf.

Goldsworthy, A., Watson, R. and Wood-Robinson, V. (2000) *Developing Understanding in Scientific Enquiry*. Hatfield: Association for Science Education.

Gott, R., Duggan, S. and Roberts, R. (2008) *Concepts of Evidence*. Durham: University of Durham School of Education.

Gott, R. and Murphy, P. (1987) *Assessing Investigation at Ages 13 and 15. Assessment of Performance Unit Science Report for Teachers: 9*. London: Department of Education and Science.

Harré, R. (1984) *The Philosophies of Science: An Introductory Survey*. 2nd edn. Oxford: Oxford University Press.

Millar, R. (1998) Rhetoric and reality:what practical work in science education is *really* for. In *Practical Work in School Science: Which Way Now?* ed. Wellington, J. pp. 16–31. London: Routledge.

National Research Council (2012) *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Committee on a Conceptual Framework for New K-12 Science Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press. Available at: www.nap.edu/catalog.php?record_id=13165.

Netz, R. (1999) *The Shaping of Deduction in Greek Mathematics: A Study in Cognitive History*. Cambridge: Cambridge University Press.

Norris, S. P. and Phillips, L. (2003) How literacy in its fundamental sense is central to scientific literacy. *Science Education*, **87**, 224–240.

Oakeshott, M. (1933) *Experience and its Modes*. Cambridge: Cambridge University Press.

Osborne, J. (2011) Science teaching methods: a rationale for practices. *School Science Review*, **98**(343), 93–103.

Pearson, D., Moje, E. B. and Greenleaf, C. (2010) Literacy and science: each in the service of the other. *Science*, **328**, 459–463.

Postman, N. and Weingartner, C. (1971) *Teaching as a Subversive Activity*. Harmondsworth: Penguin.

Tenopir, C. and King, D. W. (2004) *Communication Patterns of Engineers*. New York: Wiley–IEEE Press.

Royal Society (2014) *A Vision for Science and Mathematics Education*. London: Royal Society. Available at: royalsociety.org/education/policy/vision.

Watson, R., Swain, J. and McRobbie, C. (2004) Students' discussions in practical scientific enquiries. *International Journal of Science Education*, **26**(1), 25–46.

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