Practical inquiry in secondary science education

An evidence synthesis

THE ROYAL SOCIETY

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Practical inquiry in secondary science education: An evidence synthesis
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Executive summary

Practical inquiry relates to processes through which scientists investigate and construct understanding of the physical world. As such, practical inquiry is itself a fundamental component of scientific knowledge and culture, and it should be taught in its own right. The Royal Society has long advocated for the place of practical science at the heart of science teaching . That is because we believe that practical inquiry supports:

- development of knowledge and conceptual understanding of science;
- enjoyment of, motivation to study, and attitudes to science;
- development of scientific and wider employment skills;
- development of understanding of the norms and values of science; and
- science career aspirations.

At school, practical inquiry consists of problem-solving work that may be more or less guided by the teacher (Table 1)[i]. But schools face challenges in provisioning high quality practical inquiry, for instance because laboratory facilities, equipment, and resources are costly, on account of health and safety concerns, or because of time pressure or a shortage of specialist teachers.

This report provides a detailed synthesis of international evidence, published predominantly between 2005 and 2020, on the effects of practical inquiry in science on secondary school students (normally aged 11 – 18) mentioned above.

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[i] Gatsby Charitable Foundation 2017 Good practical science. London: Gatsby Charitable Foundation, p. 21 text (adapted).

Summary of main findings

A complex picture has emerged from more than 500 studies reviewed, because the quantity and quality of evidence available varies.

Overall, research suggests that participation in practical inquiry benefits students' knowledge and conceptual understanding of science and can support the development of physical (manipulative), process and cognitive skills (such as experimental design, making accurate observations and measurements) and wider skills (such as teamwork and communication) that are valuable in preparing students for employment and life.

There is strong evidence that the most positive impacts on motivation, learning, and skills development occur when teaching is of high quality and when there is adequate access to equipment and resources. Students are likely to benefit most:

- from repeated opportunities to participate in practical inquiry, as repeated participation is needed to ignite a long-lasting passion for science;
- when practical inquiry activities are appropriately pitched, introduced and well structured;
- when they have acquired a solid conceptual grounding before undertaking an inquiry activity;
- when practical inquiry activities involve working collaboratively;
- when plenty of time is given to reflection and discussion following practical inquiry activities;
- when explicit connections are made to real-world applications and students' lived experiences.

Most practical inquiry undertaken in schools involves 'recipe' style activities that achieve a preordained result. Such activities do not closely emulate how scientific research is conducted. However, there is good evidence to show that open-ended practical inquiry activities, such as original research projects, can provide students with authentic experiences of working scientifically and enhance their self-confidence, learning and motivation.

Further, an increasing number of studies suggest that digital technologies, such as virtual laboratories, can help develop students' scientific understanding, but evidence of their efficacy is mixed. It appears that virtual laboratories may be particularly useful in helping students comprehend abstract concepts that cannot be effectively demonstrated through conventional physical activities or in priming students ahead of carrying out work in a physical laboratory.

Areas that require more study due to a lack of robust evidence include showing that participating in practical inquiry can (i) help develop students' employability (eg critical thinking) skills; (ii) enhance their understanding of research culture in science and the values underpinning this; influence their decisions to study science at a higher level or (iii) lead them to pursue a scientific career.

Quantity and quality of research

Although practical inquiry is axiomatic to science, concerns about the quality of educational research and the robustness of evidence mean that confidence in several findings is not as strong as it should be. As a similar rapid evidence synthesis undertaken for the Gatsby Charitable Foundation in recent years concluded, 'there is a wealth of commentary on the purpose and usefulness of practical science, but very few robust studies'[ii].

These concerns, listed below, hinder the establishment of a clear consensus. Hopefully they may help guide future research in this area.

1. There is a confusing array of terminology for describing and understanding practical inquiry. The relationship between 'interest', 'motivation' and 'attitude' in the research literature is confused and unclear.
2. There is a lack of rigour among researchers in creating bibliographic records, which could mean that important studies are overlooked in meta-analyses and other evidence syntheses.
3. Sample sizes are often small and study timeframes are often too short to address research questions satisfactorily, weaknesses that probably relate to shortcomings in funding models.
4. There is a notable lack of replication, so there is very little corroborative evidence.
5. Differences in culture, in the historical approaches to teaching practical inquiry across education systems, and lack of consistency in the range of science topics investigated, make it hard to generalise findings.
6. Evidence of the impact of practical inquiry on career choice is based on students' stated intentions rather than longitudinal tracking studies.

[ii] Gatsby Charitable Foundation 2017 Good practical science, appendix 1: rapid evidence review, p.3. London: Gatsby Charitable Foundation. (See https://www.gatsby.org.uk/uploads/education/reports/pdf/gps-appendix-one.pdf, accessed 13 December 2021.)

TABLE 1

Typology of typical forms of practical inquiry undertaken by secondary school students

Confirmatory experiments, in which students do an experiment designed to confirm or apply a theory they have already met.	These are often of short[a] or standard[b] duration. For example, students using conservation of momentum to predict the behaviour of dynamics trolleys
Experiments to derive theories, in which students carry out experiments designed to reveal a theory.	These are often of short or standard duration. For example, students using laser pointers and glass blocks to derive Snell's Law of refraction
Technique development, in which students learn or develop a particular scientific technique.	These can be of short or standard duration. For example, students practising their technique in titrations.
Observation activities, in which students practice scientific observation.	These are often of short or standard duration. For example, students observing and classifying different types of birds' feathers
Investigations, in which students design an experiment to test a given question, carry it out and interpret the results, all within a fixed time-period.	These may be of standard or longer duration. For example, students investigating the relationship between voltage and current in an electric circuit.
Projects, in which students think of a question, design an experiment to test it, carry it out and interpret the results, within an extended time-period.	For example, students analysing the harmonics of the human voice to see if they correlate with ethnicity. Projects may involve collaborative research, in which students work as part of a group investigating a research question over an extended time-period, often supported by a researcher from university or industry.

[a] Short duration: less than one lesson.
[b] Standard duration: one hour long lesson.

Introduction

Humans are innately curious beings. We seek from an early age to discover and understand the world around us through exploration and experimentation. Scientists have honed this natural curiosity to create a range of methodologies in empirical and theoretical inquiry that, in its early years, the Royal Society played a central role in developing[1].

The underpinning principle behind these methodologies is to establish 'knowledge' through observation and experiment rather than trust to untested opinion or judgement.

It is important to recognise that knowledge and understanding will evolve through experimental ingenuity and change over time. This idea is enshrined in the Royal Society's motto *Nullius in verba*, roughly translated as "Take nobody's word for it". Accordingly, science is both the study of the world around us and our uncertain, ever-changing, understanding of it.

Scientific methodologies have been, and rightly remain, central to the study of science in schools in the UK and other countries. Emphasis on developing 'practical skills' was recognised as a particularly British tradition in the 1960s[2], and these were embedded into England's first statutory National Curriculum, introduced in 1989, so that students may "explore the world of science and … develop a fuller understanding of scientific phenomena and the procedures of scientific exploration and investigation"[3]. More than three decades later, one of the aims of the existing National Curriculum for Science requires ensuring: "all pupils develop understanding of the nature, processes and methods of science through different types of science enquiries that help them to answer scientific questions about the world around them"[4].

Regular, well-guided, participation in such 'science enquiries' is vital for enabling students:

- to experience and develop their understanding of scientific phenomena relating to key scientific ideas;
- to recognise the relevance of these ideas to the wider world;
- to find answers to their own questions by designing and carrying out experiments and, by doing so, understand the nature, variety, and challenges of scientific methods of investigation; and
- to appreciate that science is a creative endeavour that requires imagination, persistence, rigour and the ability to innovate.

However, the value of practical inquiry and its importance cannot be taken for granted. Science educationists have repeatedly had to argue the case for practical inquiry to be at the heart of science education. The following three chronological examples exemplify the sorts of challenges they have faced.

1. In 2011, the House of Commons Science and Technology Committee reported on concerns that health and safety legislation was leading to less practical inquiry being done in schools[5]. The Committee determined that these concerns were baseless, but that Ofsted needed to report on whether schools are suitably equipped to provide and deliver practical inquiry experiences.

2. When Ofqual proposed the reforms to GCSE and A level qualifications in England, introduced from 2015, the Council of Science and Technology (CST), which advises the Prime Minister, wrote to the then Secretary of State for Education and asserted: 'Practical laboratory work is the essence of science and should be at the heart of science learning … studying science without practical experimental work is like studying literature without reading books'[6]. These reforms established the 'practical endorsement'[7], provision for a minimum experience of practical activity within a 'knowledge-rich' (or 'knowledge-based') curriculum[8, 9].

3. More recently, the Organisation for Economic Co-operation and Development's (OECD's) analysis of its 2015 Programme for International Student Assessment (PISA) tests, which focused on assessing 15-year-olds' knowledge of science, concluded that: 'After accounting for students' and schools' socio-economic profile, greater exposure to enquiry-based instruction is negatively associated with science performance in 56 countries and economies. Perhaps surprisingly, in no education system do students who reported that they are frequently exposed to enquiry-based instruction score higher in science [and, furthermore] activities related to experiments and laboratory work show the strongest negative relationship with science performance'[10]. The OECD indicated that its reported correlation between experimental work and performance should be "interpreted with caution". However, its analysis is highly contentious and has fuelled a debate within the educational research community over the value of inquiry-based approaches to science teaching and learning, which has acquired a political dimension[11].

However, the most recent challenge to practical inquiry has been caused by the Covid-19 pandemic, which disrupted education systems the world over and adversely affected science teaching and learning[12].

Surveys of school leaders, teachers and technicians conducted by the Association for Science Education (ASE) during the pandemic in 2020 revealed an anticipated substantial reduction in the amount of traditional practical work being undertaken in schools from September 2020, with up to 20% of examination classes (GSCE and A level) experiencing no practical science at all[13]. Similarly, the Royal Society of Chemistry found that trainee and newly qualified science teachers have had little opportunity to gain experience of teaching practical classes, and this is likely to affect their confidence in running such sessions[14]. These same surveys also showed that teachers remain anxious about undertaking practical inquiry in a 'post-Covid' world.

The pandemic has shown that education – and practical subjects such as science, in particular – are vulnerable and that there is a general requirement for educational systems to develop greater resilience[15]. It has accelerated the adoption of digital technologies in education and this review also considers evidence for whether digital technologies could play a role in practical inquiry in future.

About this report

This report synthesises evidence on the impacts of practical inquiry in the sciences[iii] on secondary school students, following principles for evidence synthesis for policy established jointly by the Royal Society and the Academy of Medical Sciences, which have been specifically designed to inform policy decision-making[16]. Based on reviewing research papers and reports published mainly between 2005 and 2020, it focuses on addressing the following questions, which arose from discussions at the Royal Society.

What impact does practical inquiry have on secondary students':

- development of knowledge and conceptual understanding of science?
- development of specialist and employment skills?
- development of understanding of the norms and values of science?
- enjoyment of, motivation to study and attitudes towards science?
- progression and career aspirations in science?

Chapters 2 – 6 of this report review the evidence for impact in each of the aspects listed above and discuss limitations concerning the available research, including methodological and other concerns.

The appendices deal particularly with wider concerns about the quality of research in this area and describe the methodology used for this evidence synthesis.

[iii] For the purposes of this study, 'the sciences' incorporate biology, chemistry, physics, Earth science and environmental science. Collectively, combinations of these disciplines are commonly referred to, for instance in curricula, as 'science'. However, the term 'science' is a term of convenience, and it is important to keep in mind that each of these disciplines has its own identity.

Practical inquiry in science

There is no singular approach to practical inquiry in science[17] because scientists investigate the world around us in diverse ways[18]. The absence of a common definition, and the continuous evolution of inquiry, highlights the challenges of determining what constitutes practical inquiry[19, 20].

Any attempt to evaluate the impact of the range of practical inquiry activity undertaken in school and college laboratories or in other settings is complicated by the fact that within the educational research literature there is a wide variety of terminology used to refer to or describe it (Table 2). This range of terminology is problematic for the following reasons:

- the plethora of terms encountered is confusing;
- too often researchers neither explain nor define the terms they use; and, if they do define them, then the legitimacy of their definitions may be narrow or only apply to their paper, with them having no wider, let alone universal, currency;
- many of these terms commonly appear at face value to be synonymous. They may be used interchangeably, thereby ignoring potentially important differences in their meaning;
- many of these terms are composite: laboratory or field activities constitute the specific practical forms of inquiry this report is concerned with, but other methods exist for teaching and learning science.

Other terms, such as 'practical work' and 'practical learning', may also be unappealing: 'work', might imply toil and a lack of creativity, while 'practical learning' presumes that participation in practical activities will inevitably result in learning (intended or otherwise)[86]. There is a danger, then, of conflating the learning experience with actual learning, and of confusing intent with outcome.

Accordingly, for want of a satisfactory construct or universally accepted definition, this report favours the term 'practical inquiry' to refer to participatory activities conducted in the laboratory or in an out-of-school setting[87]. The term 'practical inquiry' emphasises this report's focus on participation in scientific activities and encompasses the physical (manipulative) and/or experimental nature of the activities as well as the associated cognitive processes involved in obtaining information, insight and scientific understanding. These activities comprise inductive or deductive approaches (Figure 1) that involve:

- making observations and measurements (individually or collaboratively);
- formulating a question based on what has been observed;
- formulating a testable hypothesis;
- planning and design of experiments and surveys;
- experimentation;
- analysing and interpreting results;
- reasoned discussion and conclusions based on the evidence gathered.

FIGURE 1

Inductive and deductive approaches to practical inquiry[88]

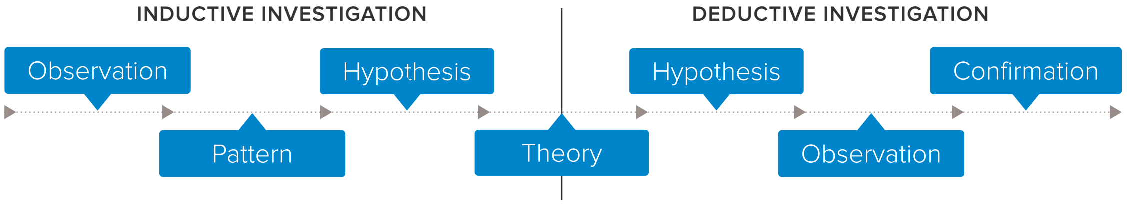


TABLE 2

Examples of terms used to describe practical inquiry activities

Term	Example source(s)
Authentic science inquiry	21, 22
Enquiry-based science	10
Explanation-driven inquiry	24
Experimentation-driven inquiry	25
Explanation-oriented inquiry	24
Full inquiry	23
Guided inquiry	23, 26, 27, 28, 29
Hands on	30, 31, 48
Inquiry approach	32
Inquiry-based approach	33
Inquiry-based experiments	34
Inquiry-based instruction	23, 35, 36, 37, 38, 40, 41, 42, 43
Inquiry-based investigations	44
Inquiry-based laboratory activities	49
Inquiry-based laboratory investigations	44, 47
Inquiry-based laboratory teaching	49
Inquiry-based learning	34, 40, 44, 52, 53, 54, 55, 56, 57, 58, 59, 60
Inquiry-based science	23, 61, 62
Inquiry-based science education	63
Inquiry-based science instruction	39
Inquiry-based teaching	41, 43, 46, 65
Inquiry instruction	40, 42, 66, 67
Inquiry investigations	68
Inquiry learning	26, 45, 51, 60, 61, 69, 70, 71
Inquiry method	31
Inquiry science	61
Inquiry science instruction	39, 64
Inquiry strategies	50
Inquiry teaching	73
Inquiry teaching method	72
Open inquiry	23, 26, 60
Project-based inquiry	73
Science inquiry	74
Scientific inquiry	18, 21, 24, 45, 51, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85

Therefore, in this report, the term 'practical inquiry' encompasses "hands-on activities using scientific techniques and procedures, and scientific enquiries and investigations"[89].

The term 'practical inquiry' is applicable across the range of teaching strategies described by the various levels of laboratory and field activities recognised, ranging from closed (teacher-directed) to open-ended (student-centred) experiences (Figure 2), which may entail problem-based, project-based and inquiry-based learning approaches, all of which are acknowledged as having close similarities[90].

Finally, given the increasing sophistication of virtual laboratories and growing independent evidence of their efficacy in teaching and learning science[91, 92], and the fact that pioneering scientific research now takes place using software and within simulated environments, this report applies 'practical inquiry' to virtual as well as physical contexts.

FIGURE 2

Different levels of practical inquiry[93, 94, 95]

Level 4 (Open-minded inquiry)	Students decide on the problem to be solved, the equipment and procedures for solving it, and conduct the inquiry themselves. They reflect on and refine their experimental procedure, and analyse and interpret data with respect to competing theories or explanations.
Level 3 (Open guided inquiry)	The teacher only provides students with details of the problem, and they work to solve it. During this inquiry process, the teacher guides students through discussion.
Level 2b (Guided inquiry)	The teacher details the problem to be solved and provides students with the equipment needed to address it.
Level 2a (Guided inquiry)	The teacher provides specific inquiry questions and procedures for students to follow.
Level 1 (Closed inquiry)	The teacher provides students with details of the problem to be investigated, the apparatus, procedures, and the solution ('recipe' style practical inquiry).
Level 0 (Demonstration)	The teacher uses classroom demonstrations to help develop conceptual understanding.

Note: This figure combines elements from diagrams in the three studies referenced.

Impact of practical inquiry on students' development of knowledge and conceptual understanding of science

2.1 Introduction

The extent to which practical inquiry increases understanding of scientific knowledge, and how this learning occurs, has long been debated in the science education literature[96]. Some, including the Royal Society, believe it is integral to the learning of science[97], and have argued their case. However, others have argued that it is ineffective or even detrimental to student progress[98, 99]. More recently, a review of evidence for the Gatsby Charitable Foundation concluded: "It is hard to identify a simple relationship between students' science achievement and their work in the laboratory. In fact, it is almost impossible to prove a causal connection between hands-on learning and increased conceptual understanding of key scientific phenomena"[100]. There is some, but not overwhelming, evidence of a positive correlation between practical and other inquiry activities and development of knowledge and conceptual understanding, taking certain factors into consideration[101, 102] (eg instructional strategies). However, efficacy varies[103] and depends on many factors, as outlined later in the chapter.

Laboratory investigations offer important opportunities to connect science discussed in textbooks and the classroom with observations and experiences. However, while it is important to learn how to conduct laboratory work and experimentation, laboratory inquiry on its own does not encourage meaningful learning[104]. Similarly, while it is important to learn how to make accurate observations, observations alone are not sufficient for learning and students do not automatically progress from observing phenomena to constructing and understanding concepts[105, 106].

This is not surprising: watching a car brake or accelerate does not automatically lead to an understanding of Newton's laws. But, when laboratory experiences are integrated with other learning experiences and incorporate the manipulation of ideas, instead of simply materials and procedures, they can promote the learning of science[107].

This chapter presents research relating to the effects of practical inquiry on students' knowledge and conceptual understanding of the sciences. Initially, evidence from global studies and meta-analyses is considered before identifying specific factors and themes that educators should consider when designing curricula or planning and teaching lessons.

2.2 International studies

The Programme for International Student Assessment (PISA) is a worldwide study conducted by the Organisation for Economic Co-operation and Development (OECD) to evaluate educational systems by measuring 15-year-old school students' academic performance. Students are scored based on their performance on a two-hour computer-based test. These scores are then scaled to account for multiple variables and create meaningful indices. The tests normally take place every three years with foci alternating between reading, mathematics, and science. The 2015 study was the most recent one to focus on science achievement. Analysis of the students' responses to questions concerning an index of nine facets of 'enquiry-based teaching' practices found that "activities related to experiments and laboratory work show the strongest negative relationship with science performance"[108] (Figure 3).

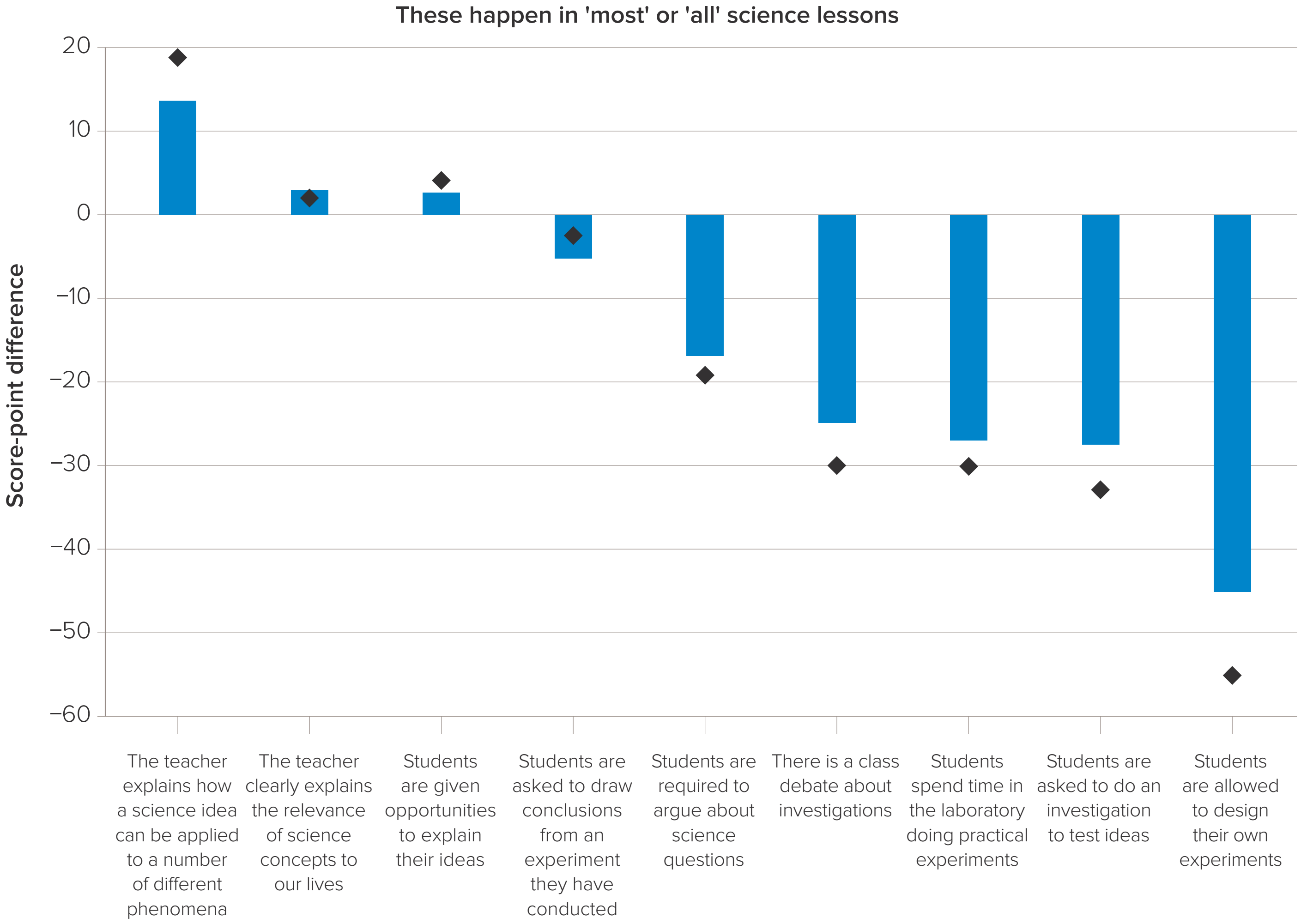
FIGURE 3

Relationship between enquiry-based teaching practices and science performance in the 2015 PISA assessment[109]. Results based on students' reports, OECD average

KEY

🟦 After accounting for students' and schools' socio-economic profile

◆ Before accounting for students' and schools' socio-economic profile (measured by the PISA index of economic, social and cultural status)



Notes:

1. The index scoring system is a composite range of measures.
2. Results based on students' reports, OECD average.
3. All differences are statistically significant.
4. Source: OECD, PISA 2015 Database, table II.2.28.

The OECD's report also stated: "Perhaps surprisingly, in no education system do students who reported that they are frequently exposed to enquiry-based instruction score higher in science". After accounting for students' and schools' socio-economic profile, greater exposure to inquiry-based instruction was negatively associated with science performance in 56 of the 72 participating countries and economies. Activities related to experiments and laboratory work were found to show the strongest negative relationship with science performance, leading the OECD to suggest:

"that some of the arguments against using hands-on activities in science class should not be completely disregarded. These include that these activities do not promote deep knowledge, that they are an inefficient use of time, or that they only work when there is good laboratory material and teacher preparation"[110].

Subsequent analyses of these and other large-scale international tests have sought to scrutinise this finding more thoroughly. For example, Jerrim *et al*. (2019) linked a nationally representative sample of 2015 PISA test results from England with the participants' records of achievement in the National Pupil Database[iv] and found, through mathematical modelling, that:

"… inquiry-based teaching has a very weak relationship with attainment in science – and that any positive effects are confined to moderate levels of inquiry combined with high levels of guidance. High levels of inquiry or unguided inquiry have no relationship with attainment at all"[111].

However, analyses of PISA 2015 data often neglect to consider the influence of wider factors such as the frequency or openness of practical inquiry activities, both of which can have a considerable influence on how effectively students learn science (see sections 2.3 – 2.5 and 2.9.4 in this chapter).

In addition, further studies using PISA data have reported that students carrying out experiments in the laboratory in some lessons have higher achievement scores than students who perform experiments in all lessons or in no lessons (see section 2.9.3). This nuances the findings of the PISA test results from 2006, which found that "hands-on activities … showed a positive relationship with science achievement"[112].

Notably, the OECD cautions that combinations of factors (including students' socio-economic status, school size, time devoted to teaching and learning science, and whether the school offers a science club) have a much greater impact on students' attainment than does their engagement in practical inquiry[113]. Effect sizes are small and the data show correlation, not causation.

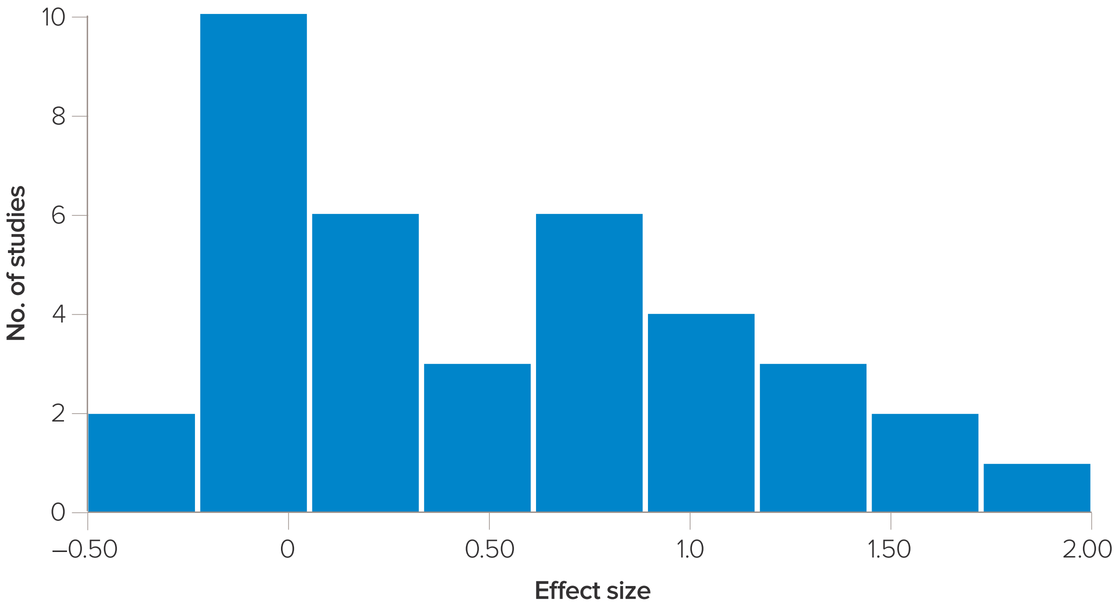
[iv] These included Key Stage 2 test data collected at age 11 (for reading and mathematics) and teacher assessment data (for science) and attainment from GCSE examinations (taken at age 16, six months following the PISA tests).

2.2.1 Evidence from meta-analyses

Meta-analyses combine the results of multiple studies on a topic to calculate an effect size that is used to signify the strength of the relationship, in this instance, between practical inquiry and learning in science. It is important to acknowledge that these studies have varying scopes and investigate different curricula, but together they suggest that practical inquiry does have a positive effect on students' knowledge and conceptual understanding of science. However, the strength of this relationship is generally quite modest and dependent on myriad factors. Figure 4 shows the range of effect sizes that are taken into account[114]. Some studies show a negative effect, some show a strong positive effect, and the majority display a very moderate effect size.

FIGURE 4

Variation in effect sizes across 37 studies[115]



Notes:

1. In the original paper the *y*-axis has been mis-labelled as 'percent'.
2. These authors state: 'These studies generally computed effect sizes by taking the difference between mean achievement outcomes for treatment and control groups and dividing by the standard deviation of the control group'.
3. Mean = 0.5.
4. Standard deviation = 0.557.

Hattie's examination of over 800 meta-analyses relating to the influences on achievement in school-aged students found that "the use of [the] laboratory and more hands-on activities has produced mixed results"[116]. He noted that effectiveness of hands-on laboratory teaching depends not only what is being measured but also on how the laboratory activity is structured and the teaching strategies used, with effect sizes ranging from very small to very large. For example, using 'the laboratory' to simply verify what has been previously presented was found to be far less effective than using it to question, explain, and encourage thinking at higher levels, utilising a variety of sources to discover answers to questions.

Another part of Hattie's synthesis reviewed the effectiveness of 'inquiry-based teaching' (an integral part of which is conducting experiments) and noted a small overall mean positive effect from four meta-analyses that, between them, covered 205 studies[117]. Experimental inquiry (pedagogy that "involves generating and testing hypotheses for the purpose of understanding some physical or psychological phenomenon") was found to have a large positive effect, although there was considerable variation between just six studies[118].

Minner *et al.*'s (2010) review of 138 papers on inquiry instruction in science found positive effects on student content learning when inquiry instruction and hands-on activities were part of the investigation cycle and when there was some emphasis on encouraging students to think actively or take responsibility for their learning. They found that "hands-on experiences with scientific or natural phenomena also were found to be associated with increased conceptual learning". Their findings indicate that teaching strategies that actively engage students in the learning process through scientific investigations are more likely to increase conceptual understanding than strategies that rely on more passive techniques such as call-and-respond formative assessment, which focuses on factual level information, and 'recipe' style procedures rather than investigations[119].

A more recent meta-analysis of 37 studies on inquiry-based science teaching reported a positive effect, with significantly larger effect sizes when activities were teacher-led[120]. Another review, of 12 studies specifically focused on students with disabilities, found inquiry-based science instruction can be effective when students are given adequate support and illustrated the importance of teachers' knowledge of their students when planning and teaching classes[121].

2.3 Teaching strategies

Different teaching strategies significantly influence how effectively teachers can impart knowledge. Students responses to different approaches vary, but meta-analyses can help identify methods that are most effective for the majority of them.

One review of teaching strategies in science[122] found a medium positive effect size for 'Inquiry strategies' (where "teachers use student-centred instruction that is less step-by-step and teacher-directed than traditional instruction; [and] students answer scientific research questions by analysing data") and a similarly positive effect size for 'Manipulation strategies' (where teachers provide students with opportunities to work or practise with physical objects (eg developing skills using manipulatives or apparatus, drawing or constructing something)). The use of 'Enhanced context strategies' that engage students' interest and make learning relevant by presenting material in the context of real-world examples and problems had a very large effect size and was the most significant of all those investigated (Table 3). Collaborative learning strategies, where teachers arrange students in flexible groups to work on various tasks (eg conducting laboratory exercises, inquiry projects, discussions) were also found to have a large effect on student learning and are widely considered a core part of practical inquiry. With the exception of 'Enhanced context strategies' (which were notably more effective than the other strategies), the range of results for many of the other teaching strategies overlapped and were judged not to markedly differ from each other.

TABLE 3

Ranking of teaching strategies[123]

Strategies	Effect size	Rank
Enhanced context strategies	1.48	1
Collaborative learning strategies	0.96	2
Questioning strategies	0.74	3
Inquiry strategies	0.65	4
Manipulation strategies	0.57	5
Assessment strategies	0.51	6
Instructional technology strategies	0.48	7
Enhanced material strategies	0.29	8

2.3.1 Using scaffolding to support students

Students can learn more when they are given appropriate support and guidance. This is known as scaffolding. A supportive, temporary framework, like one used in constructing a building, allows a much stronger structure to be built within it. This is well known in the education sector and is founded on the research of Piaget, Bruner and Vygotsky[124].

When practical inquiry is unstructured and students are not adequately supported, it can easily become too difficult[125], especially for younger learners[126] or for those with little prior knowledge of the topic. When students are working in the laboratory there is a vast amount of information to take in. Working memory, where a limited amount of information is temporarily stored, can quickly become overloaded, placing cognitive demands on students that they may not be equipped to handle[127, 128, 129]. Students can become preoccupied with technical and manipulative details that consume most of their time and energy and distract from the intended purpose of the activity. This can hold back or even negatively influence learning, for example, by establishing misconceptions that then need correcting. There is also research that suggests students learn less when they are tasked with doing more demanding and difficult experiments[130]. Jerrim *et al*. (2019) report that inquiry "is less effective than more direct forms of instruction [in improving attainment] … except for in cases when inquiry is highly guided". They also found "tentative evidence that high [levels of] inquiry delivered in conjunction with high [amounts of] guidance may have a small positive impact upon science achievement"[131]. Moeed *et al*. (2016) found that students are more likely to learn what is intended when teachers plan a limited number of specific learning goals from a practical inquiry activity[132].

Types of scaffolding and support

Several studies show that with appropriate support students participating in practical inquiry work are able to learn the same or more than those in control groups. The effectiveness of different scaffolds changes according to various factors, such as specific learner characteristics. A one-size-fits-all approach is not suitable.

Several studies demonstrate that a practical or other inquiry activity is more likely to be successful when students have prior knowledge of the topic and/or procedures involved that can act as a framework for supporting new knowledge[133, 134, 135, 136]. This connects to other findings suggesting that younger and less-experienced students need more explicit guidance than older students[137, 138]. One study showed that problem solving scaffolded by a laboratory guide, as well as incremental scaffolds, led to higher retention scores than unguided problem solving[139]. Another found that the use of incremental scaffolds only helped some students acquire more conceptual and procedural knowledge, but such scaffolds were seen as a valuable tool for differentiation within classes, especially when promoting the conceptual and procedural skills of students with low prior knowledge[140].

Teacher intervention in providing guidance in how to interact during cooperative, inquiry-based science appears to be critical to helping students engage in higher-level thinking and learning[141, 142].

2.3.2 Teacher-led and student-centred learning

As discussed in the last subsection, students need adequate support and guidance to make progress with their learning. One way in which the amount of support or guidance given can be varied is for a teacher to determine whether the students should lead their own learning. Again, this is not a mutually exclusive choice and teachers can use both approaches within their lessons.

Meta-analyses show that teacher-led studies have a larger positive effect than student-led studies when these are part of inquiry teaching[143]; however, there is considerable variation between countries[144]. Other work suggests that guided inquiry (which sits somewhere between student- and teacher-led instruction on the continuum – see Figure 2 in the previous chapter) is much more effective than teacher-led instruction alone[145] or verification style laboratory exercises[146]. Student-led learning is not necessarily inferior, but its efficacy depends on a number of factors, such as what is being taught and student characteristics. Studies have shown that more demanding student-centred practices are more beneficial for high-achieving students than for low-achieving students, who may lack the basic vocabulary and conceptual understanding essential for engaging in meaningful self-regulated learning[147]. Teacher intervention is also important in providing guidance on how to interact during cooperative, inquiry-based science and appears to be critical in helping students engage in higher-level thinking and learning[148].

2.3.3 The importance of contextualising learning

It is important for learning to be contextualised: learners construct knowledge by solving genuine and meaningful problems[149, 150]. New knowledge needs to fit within students' existing conceptual framework, building on their prior learning as well as the wider world around them. Students should be able to evaluate sociocentric issues in their lives outside and beyond school[151].

Contextualising learning is important not just as a principle, but also because it can have significant positive effects on students' ability to learn. One meta-analysis of teaching strategies revealed that 'Enhanced context strategies', such as relating topics to previous experiences or making learning relevant to students by presenting material in the context of real-world examples and problems, had the largest effect size of all the strategies measured[152] (see Table 3).

Another – longitudinal – study demonstrated that students who were exposed to more student-centred environments that contextualised science in the real world outperformed other students in mandated state science assessments[153]. Other studies have found that making learning relevant and personally meaningful is especially powerful for students with low success expectations[154]. Analysis of PISA data shows that the highest levels of achievement are reported when teachers explain how a science idea can be applied and clearly show the relevance of science concepts to students' everyday lives[155]. Numerous other studies highlight the value of giving more learning time to apply understanding of concepts to real-world contexts[156, 157, 158, 159, 160, 161].

2.4 The value of authenticity

Authentic science is rarely explicitly defined and has been described as an “elusive and problematic notion with diverse meanings and implications for curricula”[162]. Simply put, authentic science refers to the research and practice that real scientists ‘do’[163, 164] and the ‘ordinary practices of the culture’[165]. It includes: asking questions, planning and conducting investigations, drawing conclusions, revising theories, and communicating results[166].

There are studies that find authentic science teaching can enhance science content knowledge[167], catalyse learning[168] and improve long-term retention of learning and performance on state-mandated assessments[169]. While more high-quality research is needed in this area, it is difficult to argue (and not a single paper reviewed for this report does) that science education should be less authentic.

2.4.1 Independent research projects

Studies invariably claim that science taught in schools should strive to be more authentic and studies on independent research projects (IRPs; see Box 1) often credit their positive impact to their authentic nature. This is likely because authentic science is usually well contextualised and has a positive effect on student engagement and motivation (see Chapter 3) and has also been associated with increasing scientific understanding[170].

Bennett *et al.*’s (2018) recent systematic review of IRPs across 12 countries found that IRPs were most prevalent among 16 – 19 year olds. These researchers reviewed evidence that suggested that IRPs are widely perceived as benefiting students’ learning, attitudes towards science, motivation to pursue scientific careers, as well as increasing participation in science among traditionally underrepresented groups. However, they also concluded that the design of research into the effects of IRPs on students could be improved[171].

BOX 1

Independent research projects

Independent Research Projects (IRPs) are extended, open-ended, investigations that enable students to gain authentic experiences of thinking and acting like scientists and by conducting research related to 'real world' problems. While teachers will often play a significant role in enabling and guiding these projects, some are student-led investigations (such as the CREST Awards or the Extended Project Qualification). They typically last between six weeks and one year and participation in them is normally voluntary.

National providers of IRP schemes in the UK include the CREST awards (run by the British Science Association), the Institute for Research in Schools and the Royal Society's Partnership Grants scheme.

CREST Awards

The CREST Awards programme is a national awards scheme run by the British Science Association that offers 5 – 19 year olds a flexible range of opportunities to pursue their own scientific investigations, with support from teachers and, at higher levels, academic or industrial scientists and engineers. Awards are made at six levels.

Institute for Research in Schools

The Institute for Research in Schools offers secondary school students opportunities to work collaboratively with practising scientists and engineers on cutting-edge research projects. It also seeks to provide teachers and technicians with the support they need to contribute to, and mentor, scientific research with their students, and to promote and facilitate sustained research collaborations between schools and universities.

The Royal Society's Partnership Grants scheme

Through funding from the Department for Business, Energy and Industrial Strategy (BEIS)[v], the Partnership Grants scheme provides schools and colleges with up to £3,000 to run investigative projects in science, technology, engineering or mathematics (STEM) in partnership with professionals from academia or industry. Students work collaboratively with practising scientists and engineers on investigative research projects, from which they gain understanding of the mechanics of how science is done. The scheme seeks primarily to help students develop the key skills needed for future scientific careers and demonstrate the range of STEM career opportunities available. It also seeks to foster long-term sustainable relationships between schools and STEM partners, help teachers feel part of the scientific community, and encourage STEM professionals to develop school engagement skills.

Nuffield Research Placements

Nuffield Research Placements provide students in Year 12 or equivalent (aged 16+) with opportunity to engage in supervised independent research in collaboration within a professional working environment, such as a university or museum.

Extended Project Qualification

The Extended Project Qualification (EPQ) is a standalone qualification in England, equivalent to half an A level, which offers post-16 students an opportunity to undertake a substantial and creative, self-driven, project that develops valuable planning, research, critical thinking and problem-solving skills. It is not necessarily a practical inquiry. Research using data from the National Pupil Database has shown that 16 – 18 year old students in schools and colleges who gain an EPQ are more likely to attain a good degree, and that undertaking an EPQ may enhance performance in A levels[172].

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v. In 2023, BEIS was replaced by the Department for Energy Security and Net Zero, Department for Science, Innovation and Technology, and Department for Business and Trade.

2.5 Closed and open-ended learning activities

The extent to which a lesson in the laboratory consists of closed or open-ended activities may have a significant effect on student learning. However, the precise nature of impact is hard to predict, for the following reasons.

With closed activities, the expected outcomes are known in advance and students replicate recommended procedures, as prescribed or demonstrated by the teacher. These activities are especially valuable for teaching skills and conveying specific knowledge. For example, research has shown that teacher demonstrations can be effective in preparing students to answer practical-themed examination questions, especially when circumstances prevent hands-on practical work (such as following Covid-19 protocols)[173].

Open-ended laboratories require students to design experiments, make observations and construct models based on data. Students work collaboratively with their peers to solve problems "that do not have one correct approach or solution"[174]. But while open-ended practical inquiry is frequently acknowledged by science educationists as a more authentic way of 'doing' science[175], some students can find it frustrating, in part because the outcome of the inquiry is not straightforward. In referencing a study by de Jong *et al*. (2005)[vi], Schuster *et al*. (2018) note that if the task is too open-ended, students may "have difficulty forming suitable questions to explore, choosing variables to work with, linking hypotheses and data, and drawing correct conclusions from experiments"[176]. They may become lost and, without appropriate guidance, develop misconceptions.

Students' performance may vary from one investigation to another depending on the subject matter, context, openness and the complexity of the problem being tackled[177, 178, 179], as well as the extent of their prior learning, their ability (both actual and perceived) and the amount of teacher support available. As a result, "teachers may need to spend considerable time scaffolding students' content and procedural skills together"[180] before they can relinquish control in the laboratory[181].

Some studies suggest that student investigations, of themselves, are not effective if students are left to their own devices[182]. A study that contrasted 'discovery'-based learning approaches (open-ended learning focused on active engagement with physical science phenomena and experimentation) with direct instruction (teacher demonstration and worksheets) found no significant difference in students' understanding of concepts related to controlling variables in experiments immediately following the instruction. However, in a follow-up assessment two weeks later, the retention of concepts related to controlling variables in experiments was better for students who received the discovery teaching.

Additionally, it has been shown that students with a learning disability that received discovery teaching outperformed their counterparts who received direct instruction in the performance-based assessment of their ability to generalise their learning[183]. Other studies show inquiry and direct methods produce comparable results[184].

[vi] de Jong, T, Beishuizenm, J, Hulshof, C, Prins, F, van Rijn, H, van Someren, M, Veenman, M, & Wilhelm, P 2005 Determinants of discovery learning in a complex simulation learning environment. In Cognition, education, and communication technology (eds P. Gardenfors & P. Johansson), pp. 257–283). Mawah, NJ: Erlbaum.

However, studies have found in favour of open-ended, explorative teaching approaches when compared with narrower deductive approaches[185], particularly for older students[186, 187, 188]. Moving from teacher-directed investigations to a more open-ended methodology helps develop critical thinking and not just manipulative skills[189]. Open-ended experiments are frequently seen as a more authentic way of doing science as many of the problems professional scientists have to solve are open-ended[190, 191, 192] (see Chapter 5).

In reality, open and closed approaches to practical inquiry are complementary extremes of a continuum (see Figure 2 in the previous chapter). Teachers must decide where a lesson, or sequence of lessons, should fit on this spectrum, based on the needs of their students and the requirements of the curriculum. Even small amounts of open-ended learning (eg students designing but not carrying out their own experiments) are seen as beneficial[193]. If they are to succeed, open-ended practical inquiry projects require that students receive significant support and encouragement from their teachers. This is particularly true when students have only just been introduced to this style of inquiry[194]. Other studies have shown success in mitigating the drawbacks of open-ended learning by using a limited number of investigations and techniques so that procedures become routine[195].

2.6 Collaborative learning

Collaborative learning involves students engaging in a common task, working jointly to co-construct meaning or solve a problem. It is widely considered to be an important aspect of practical inquiry[196]. It can be used to teach skills (see Chapter 4) enhance motivation (see Chapter 3) and can also have a positive impact on learning[197].

The idea that learners influence one another when learning together underpins the theory of collaborative learning[198]. Studies have found group work to be more effective than individual working[199] (but less effective than peer tutoring) when conducting practical inquiry[200]. Some studies have shown the effectiveness of group work can vary depending on the composition of the group: students tend to have improved learning outcomes when the groups they work in are flexible and heterogeneous[201, 202].

In group work, there is always a risk that one or more participants will take on less than their fair share of responsibility or contribute less to the collective endeavour. Participants who work hard in groups run the risk that others will free ride on their efforts; the ‘free rider’ effect and the ‘sucker effect’ are frequently found in practice[203]. The possibility of being a ‘sucker,’ contributing to the collective good when nobody else does, may lead individuals to withhold effort as a means of restoring equity and avoiding being a ‘sucker’ to others’ ‘free riding’. This can have implications for students’ motivation as well as their attainment. The identification of these effects demonstrates the critical importance of appropriate scaffolding and teacher support in maximising the potential of all students to participate in and learn from collaborative working.

2.7 'Hands-on' and 'minds-on'

It is well established that more effortful cognitive processing leads to better retention of information[204]. Ideas and explanations do not simply 'emerge' from data when students conduct experiments or undertake practical activities[205]. Simply 'doing' with objects and materials or observing phenomena, without a clear purpose and mental focus, is unlikely to lead to productive learning about scientific ideas and methods[206].

Practical inquiry might be made more effective in developing students' conceptual understanding if teachers adopt a 'minds-on' as well as a 'hands-on' approach[207, 208] and explicitly plan how students link these two essential components of practical inquiry[209]. Students need to actively think about and participate in the investigation process to increase their conceptual learning of science[210, 211, 212]. Lessons should incorporate explicit strategies to help students formulate explanations[213] and make links between their observations and scientific ideas. Attempts to improve the effectiveness of practical inquiry by encouraging teachers to change from a predominantly 'hands-on' approach to one that strikes more of a balance between being 'hands-on' and 'minds-on' have been mixed. Training can raise teachers' awareness of the issue, but they will need ongoing support over an extended period of time if they are to change their practice[214].

2.8 Reflection and discussion

Another crucial aspect of meaningful practical inquiry is ensuring that students have opportunity to reflect on their findings and clarify understanding with their peers[215, 216, 217, 218]. When too much time and attention are focused on data gathering[219], without reflecting on previous knowledge, meaningful learning and successful transfer of knowledge are less likely[220].

Discussion can encourage students who regard practical inquiry as an amenable low-demand approach to learning[221] to engage more closely with complex ideas, and actively construct their knowledge. This is preferable to leaving it to someone else to tell them firstly what to do and ultimately what they have found out[222].

Discussion therefore appears to be a worthwhile component of practical inquiry in all but the most straightforward tasks. There are benefits in encouraging discussion by frequently allocating specific time in lessons for it[223].

2.9 Other factors

2.9.1 Facilities and resources

Access to resources and facilities impact the range and quality of practical inquiry schools can provide. Teachers “need good laboratory space if they are to conduct high-quality practical classes”[224]. Indeed, the OECD’s PISA study found that “students in schools whose principals reported a well-equipped and well-staffed science department generally perform better in science”[225].

2.9.2 Quality of teaching

The importance of high-quality teaching cannot be overstated. Teacher quality is a more influential factor than any mode of learning. Expertly designed instructional units, engaging lessons and good, inspiring teaching (including guidance, support and feedback) are as, if not more, important for helping students develop their understanding than whether or not a lesson has a practical component[226].

Differences in teacher effectiveness have been found to be the dominant influence on students’ academic progress. However, identifying and isolating the specific characteristics that influence teacher effectiveness and thereby student achievement is problematic[227, 228, 229]. There are many factors to consider (Figures 5 and 6) and students respond differently to each of these. Longitudinal studies repeatedly find that teacher quality and continuous professional development are key for improving learning[230, 231, 232, 233, 234].

FIGURE 5

Attributes of a good teacher[235]

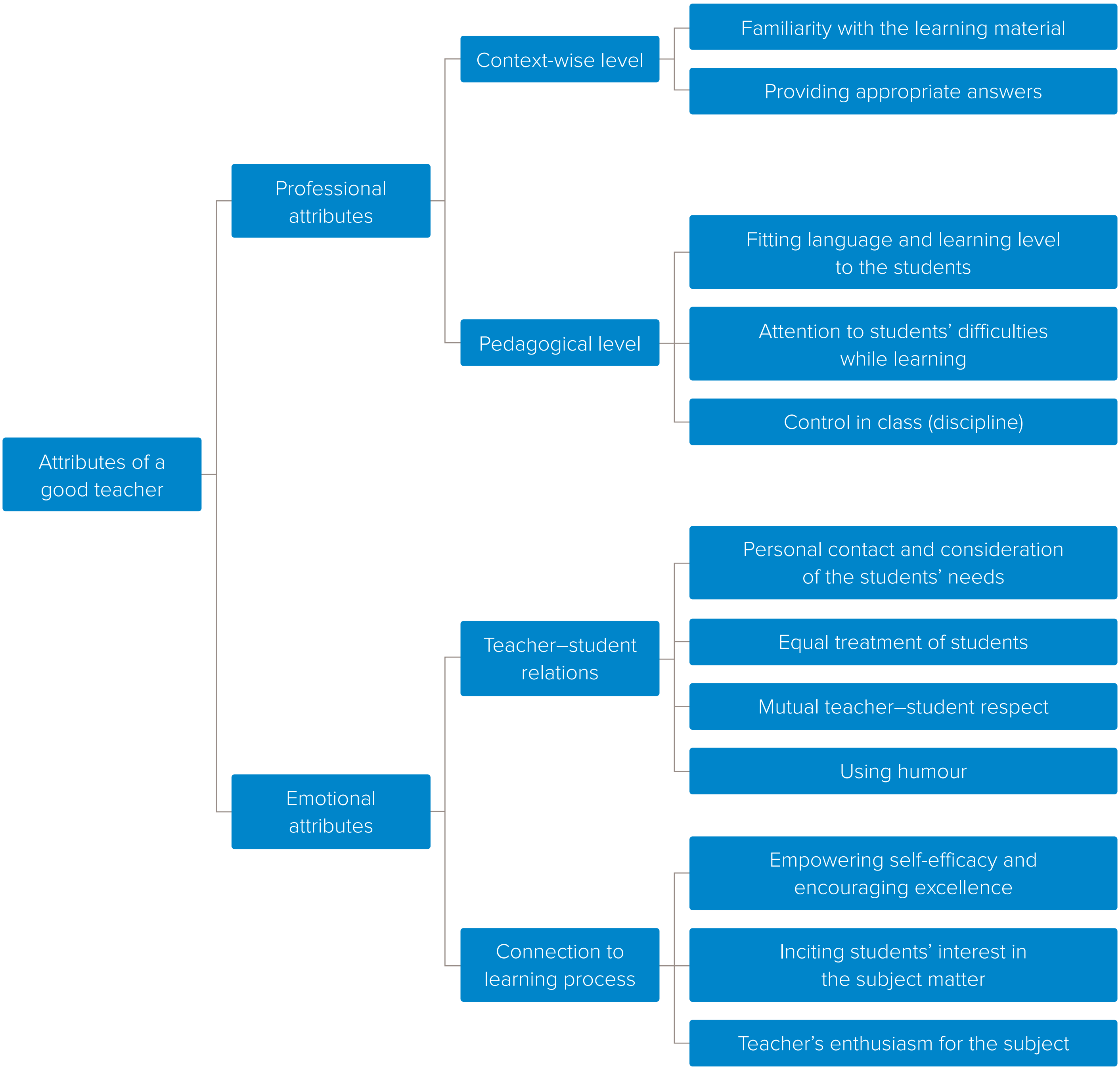
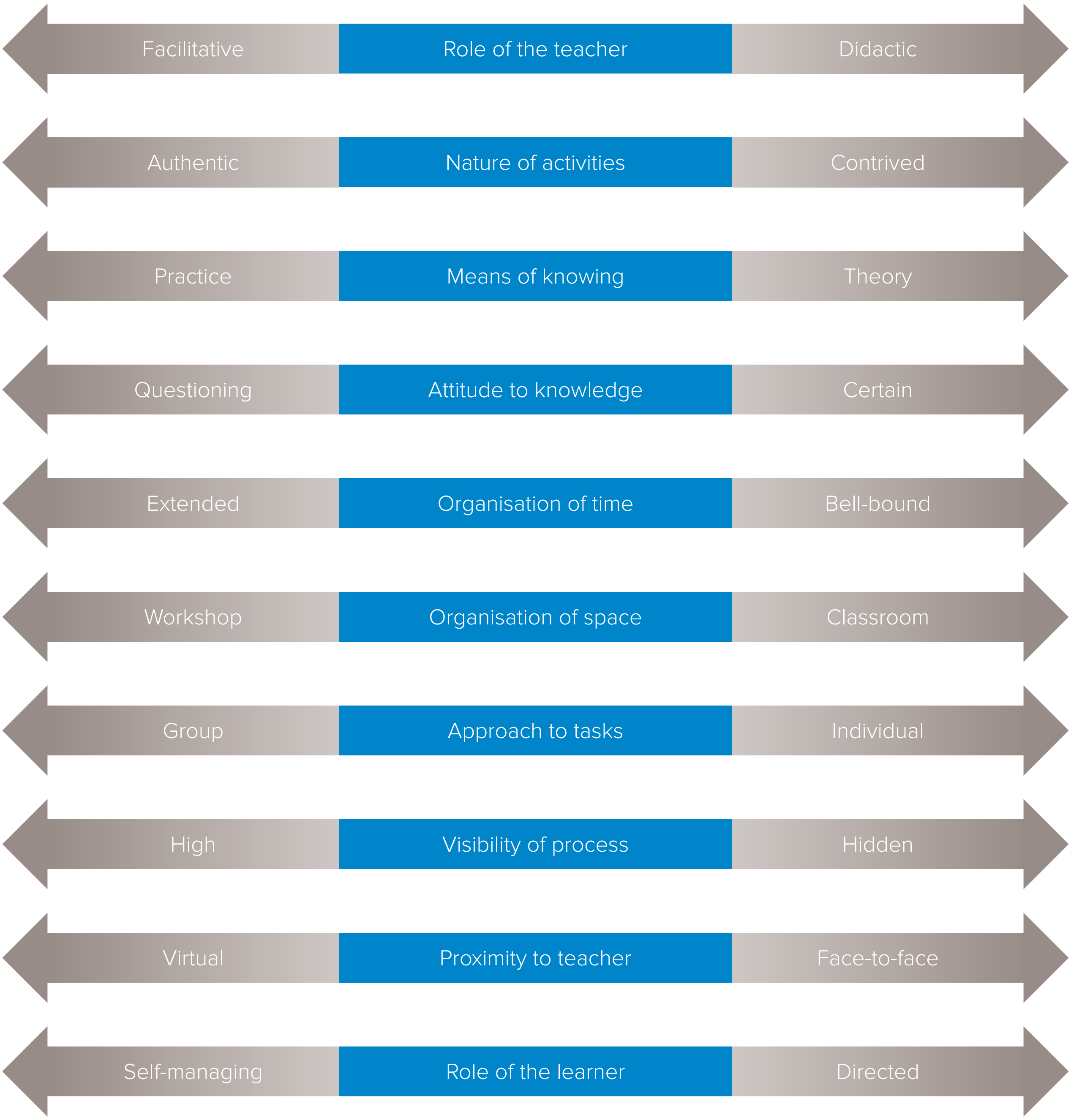


FIGURE 6

Ten dimensions of decision-making[236]



Facilitative	Role of the teacher	Didactic
Authentic	Nature of activities	Contrived
Practice	Means of knowing	Theory
Questioning	Attitude to knowledge	Certain
Extended	Organisation of time	Bell-bound
Workshop	Organisation of space	Classroom
Group	Approach to tasks	Individual
High	Visibility of process	Hidden
Virtual	Proximity to teacher	Face-to-face
Self-managing	Role of the learner	Directed

2.9.3 Frequency of practical inquiry

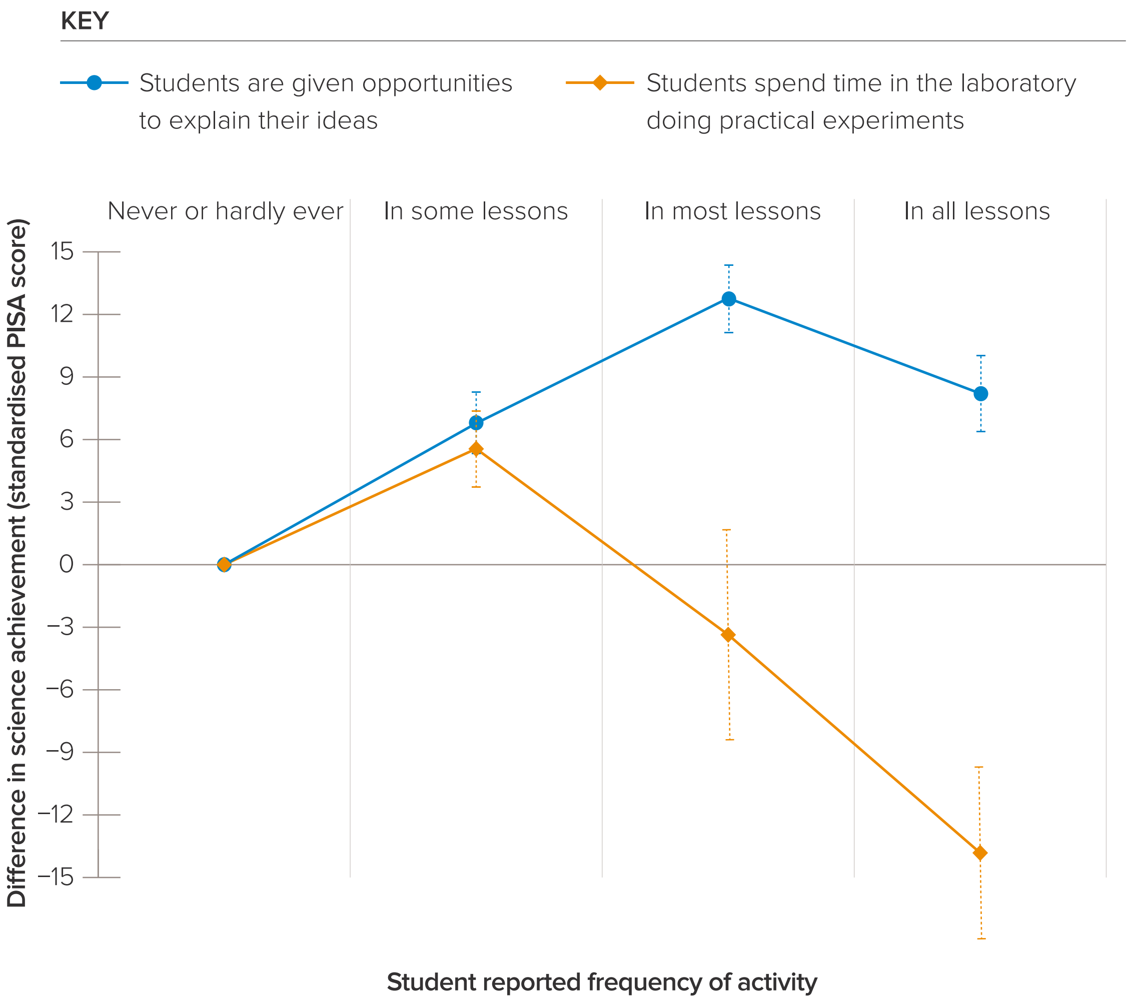
The effect of practical inquiry on student attainment also depends on how frequently students carry out these activities. Nuanced analysis of the OECD's PISA data shows a blend of inquiry-based and teacher-directed instruction has the best outcomes[237]. There is a non-monotonic relationship between the amount of practical inquiry teaching and student achievement: students who carry out experiments in the laboratory in some lessons have higher achievement scores than students who perform experiments in all lessons or in no lessons (Figure 7)[238]. Another study using the same PISA data, focusing on the frequency of inquiry-based teaching in England, found a very weak relationship with attainment in science (with any positive effects being confined to moderate levels of inquiry combined with high levels of guidance)[239].

Other studies on American[240] and South African[241] students found more frequent practical work had a positive association with student achievement. Recently published research in England has concluded "doing practical work either every lesson or very rarely is negatively associated with students' scientific literacy"[242].

Overall, this suggests there is an optimal frequency of practical work, where it is undertaken in some, but not most lessons. However, the evidence available currently does not enable a specific designation. Still, the optimal frequency would give students time to discuss, reflect and consolidate their learning, and teachers the opportunity to correct misconceptions and teach new material.

FIGURE 7

Inquiry-based approaches exhibiting a non-monotonic relationship to achievement[243]



Note: error bars represent +/– 1 SD.

2.9.4 Duration and variety of practical inquiry experiences

Practical inquiry activities vary in type and length (Table 4) and teaching may comprise more than one type of activity. Teachers need to be able to judge what sort of practical activity would best suit and engage their students. As the Gatsby Charitable Foundation has stated: “There is no single, best type of practical activity: the important thing is that the teacher knows why they are doing it and has carefully planned how to introduce it and follow it up”[244].

2.9.5 Assessment-driven school environments

Although students’ exposure to practical inquiry in science might suffer if it were not assessed, several international studies find that students in education systems that are driven by high stakes assessment, such as England’s[246, 247], are exposed to a narrower experience of practical inquiry than is desirable[248, 249, 250, 251]. Over-emphasis on testing limits students’ exposure to the full range of methodologies used by practising scientists and standards-based assessment. Use of planning templates, exemplar assessment schedules and restricted opportunities for full investigations in different contexts, tends to reduce student learning about experimental design to an exercise in ‘following the rules’[252].

Many teachers feel compelled to cover the entire curriculum to ensure that all topics are taught prior to assessment. However, the coverage of breadth, at the expense of depth, does not always benefit them: “retention is minimal and students fail to gain the ability to think critically, work collaboratively, solve problems, and ask questions about the world around them”[253].

2.9.6 Virtual laboratories

The impact of virtual laboratories on student learning is a growing area of interest. The overall findings from a number of studies suggest that simulations can be as effective, and in many ways more effective, or more enjoyable[254], than traditional (ie lecture-based, textbook-based and/or physical hands-on) instructional practices in promoting gain in science content knowledge[255, 256, 257, 258, 259, 260, 261]. Many reasons have been given for this, for example that students can concentrate on underling principles rather than on the mechanics of laboratory setup, and data collection or software can draw attention to the most relevant aspects of an experiment[262].

However, some studies that compare the effectiveness of virtual laboratories with physical experiments on students’ learning have found no significant benefit of the former[263, 264]. Researchers are still measuring the effectiveness of simulated laboratories for all standard education laboratory goals, including skills and motivation. Some suggest that laboratory simulations can be effectively used to supplement rather than replace traditional hands-on laboratories[265, 266].

A review of the research on the value of virtual labs concluded: “When directly comparing physical and virtual experimentation, several studies have found no significant and consistent differences between learning from simulations and physical laboratories… However, there have also been instances where the use of virtual laboratories has better supported students’ learning than physical laboratories…”[267].

TABLE 4

Typology of typical forms of practical inquiry undertaken by secondary school students and their expected usual duration[245]

	Typical forms of practical inquiry					
	Confirmatory experiments (designed to confirm or apply a theory)	Experiments to derive or reveal a theory	Technique development (to developing scientific skills)	Observation activities (for practising scientific observation)	Investigations (involving experimental design to test a given question, carry it out and interpret the results within a fixed time period)	Projects (student-led investigations in which students come up with a question they want to address and conduct an investigation lasting more than a week)
Short (less than one lesson)	✓	✓	✓	✓		
Standard (one hour-long lesson)	✓	✓	✓	✓	✓	
Long (three or four lessons in a week)					✓	
Extended (more than one week)						✓

2.10 Conclusions

Practical inquiry can have a positive impact on students' learning, provided the right balance can be struck between, in the OECD's language, 'teacher-directed instruction' (wherein the teacher explains and demonstrates scientific ideas, discusses questions, and leads classroom discussions) and 'inquiry-based teaching' (which includes a diverse range of practices from conducting practical experiments to understanding how science can be applied in real life, to encouraging students to create their own questions)[268].

There are several conditions that will affect this balance. Practical inquiry should be appropriately scaffolded for students, who should ideally have some prior knowledge related to the activity before starting it. It should be authentic and contextualised, with teachers making explicit connections to real-world applications and to students' lives. Students should have the opportunity to work collaboratively, and activity should be structured so that all students have their 'minds-on' as well as their 'hands-on' the task. There must be enough time for discussion and reflection on the activity, with appropriate consideration given to the amount of lesson time dedicated to undertaking practical inquiry. Finally, practical inquiry should be overseen by expert teachers who are given adequate and appropriate professional development and enabled to focus on teaching high-quality lessons rather than merely preparing students for standardised assessments.

2.11 Limitations

In addition to the confusing array of terminology used to describe the nature of practical inquiry (see Table 2 in the previous chapter), and the lack of clarity in referring to other approaches to teaching and learning science, there are some significant (i) semantic and (ii) methodological difficulties associated with seeking to measure the impact of practical inquiry on students' learning.

2.11.1 Semantics

'Learning' may relate to knowledge gain (in particular, the ability to retrieve memorised factual information, measured through testing and recorded as 'attainment' or 'achievement') or to demonstrable understanding of concepts (for instance, through assessable problem-solving) or to demonstration of procedural skills. Research studies do not always clearly differentiate between them.

2.11.2 Methodological difficulties

Length of research studies

Much educational research focuses on immediate responses to interventions (measured through comparing the results of pre-tests and post-tests), and few studies have any longitudinal component to them (eg a delayed post-test to assess retention over a longer time-scale). There is no consistency or standardised practice in determining intervals between the initial post-test and the subsequent test and there appears to be no clear expectation of how long students might reasonably be expected to retain new knowledge they have acquired. As such, there is currently very little research that helps us understand the effect of practical inquiry on the retention of knowledge and conceptual understanding of science over time.

Measurement of knowledge gain or development of conceptual understanding
It is not possible to directly measure the impact of practical inquiry on performance in written national examinations, so alternative methodologies must be used in order to shed light on this.

Except for international programmes of student assessment, there is no standardised method for assessing students' knowledge or conceptual understanding, and the very individual nature of research studies, with very few attempts at replication, makes it impossible to make robust inferences and to draw direct comparisons. Very few researchers explain in their published papers specifically how they measured the effectiveness of an intervention.

The PISA tests themselves have a number of shortcomings, such as their inability to "measure important soft skills or non-academic outcomes, and [their vulnerability] to behaviors such as teaching to the test and gaming the system"[269]. In addition, Jerrim *et al*. (2019) highlight that these tests are cross-sectional (taken at a single point in time) and do not control for measures of prior attainment[270]. Further, Cory *et al*. (2020) have drawn attention to the fact that the PISA data on the efficacy of 'enquiry-based instruction' are entirely student-reported and that the quality of this information may be "influenced by many factors, including 'students' interpretation of the individual [question] items and their individual motivation to complete the assessment accurately"[271].

This, together with the fact that PISA data are descriptive, makes it impossible to establish causally "whether observed patterns of inquiry-based instruction directly impact or result in observed levels of students' science achievement". Similarly, new research has recently emerged that challenges the OECD's assertion that enquiry-based science instruction has a negative impact on performance, on the following grounds:

i. 'analyses should account for the multidimensionality of the PISA enquiry-driven instruction index;

ii. linear models may not accurately describe the relationship between student-reported frequencies of inquiry-based instruction and scientific literacy scores, so other models should be explored;

iii. measurement invariance for students from different SES [socio-economic status] quartiles suggests that either the items or the efficacy of inquiry-based instruction vary for students from different groups and a more nuanced perspective is needed before developing recommendations; and

iv. [that] student interpretations of the items and response space require more study if we are to use the questionnaire responses to describe the activities students have in mind and their frequencies'[272].

Impact of practical inquiry on students' enjoyment of, motivation to study and attitudes to science

3.1 Introduction

In their seminal review of literature published between 1984 and 2004, Hofstein and Lunetta complained about researchers' "failure to examine effects of various school science experiences on students' attitudes" while nonetheless asserting "that laboratory work is an important medium for enhancing attitudes, stimulating interest and enjoyment, and motivating students to learn science"[273].

That failure has been addressed to an extent within international literature published in the subsequent 20 years or so. Various studies have been published that investigate students' affective responses to engaging in practical inquiry in science, including their enjoyment, interest, engagement, motivation and attitudes as well as their personal values, beliefs and self-perceptions (eg of their own competence). It stands to reason that these affective responses to practical inquiry inform cognitive effects (acquisition of knowledge and conceptual understanding), subject choices and, potentially, career aspirations (explored in Chapter 6). This chapter is concerned with understanding whether engaging in practical inquiry affects students' enjoyment and motivation to study science, and their interest in and their attitude towards (desire to engage with) science.

3.2 Mapping the affective domain

Figure 8 provides a schematic illustration of how the various affective responses described in the literature relate to engaging in practical inquiry. It illustrates the complex interplay between different emotional and behavioural responses that over time, together with cognitive influences (notably experience-informed perceptions of practical inquiry and assessed performance), will shape whether and how a student is motivated and their attitude (to learning a particular topic, to a particular scientific discipline or to science in general)[274].

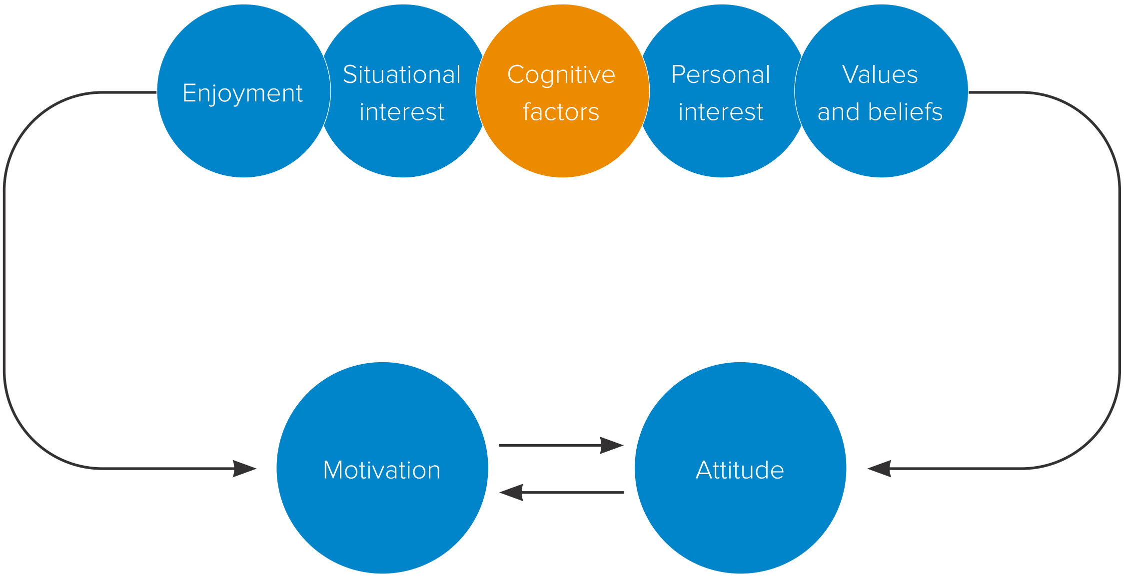
Enjoyment and interest (which affect motivation) and motivation itself will have an influence on attitude. Similarly, attitude will impact motivation and vice-versa. These responses will also be shaped by values and beliefs that have been categorised by Bergin (1999) as:

- belongingness (cultural value, identification and social support);
- emotions (positive or negative feelings towards something);
- own sense of competence[vii];
- relevance to achieving a personal or a given goal; and
- background knowledge[275].

[vii] Competence is informed by self-efficacy, defined by the OECD as 'competence in performing science-related tasks'. (See https://www.oecd.org/pisa/pisaproducts/42025182.pdf, p. 16, accessed 15 December 2021).

FIGURE 8

Schematic of the components of the affective domain and their interrelationship



3.3 Impact of practical inquiry on students' enjoyment of science

Students' enjoyment of practical inquiry has been an aspect of various studies. These studies normally relate to students' responses to interacting with scientific materials and equipment, but some studies also focus on the extent to which student enjoyment (or attitude) is mediated by the environment in which they are undertaking practical inquiry[276, 277, 278, 279, 280]. For example, practical inquiry is considered more 'fun' when students are working cooperatively and autonomously[281] as well as when it involves novelty and physical activity[282].

3.4 Impact of practical work on students' interest and motivation

The term 'interest' may "refer to either a selective preference for a particular domain of study or focused attention upon a particular situation" and has been associated with increased memory, greater comprehension, and deeper cognitive engagement and thinking[283].

Research into students' interest may relate their responses to participating in a particular experiment or their professed interest in science resulting from such participation. In both cases, it may be possible to identify the reactions as originating from 'personal' (or individual) or 'situational' interest.

3.4.1 Situational interest

Situational interest has been described as "interest that is stimulated in an individual as a consequence of their experience being in a particular environment or situation ... such as, for example, when a pupil undertakes practical work within a science laboratory"[284].

Palmer (2009) investigated situational interest among a group of nearly equal numbers of 14 – 15 year old students across five Australian schools. He found that levels of situational interest fluctuated during lessons and were much higher during participation in experimental work (including proposing investigable questions, making observations and explanations, and reporting), particularly the 'hands-on' aspect, rather than when students were copying notes. This was the case among both higher- and lower-attaining students, and the levels of situational interest recorded were similar. Palmer suggested that situational interest is powerful and "has the potential to arouse the interest of nearly all the students in a group, regardless of their pre-existing interests and motivational beliefs". However, he acknowledged that while situational interest may be influenced by the quality of teaching, it is transient and ephemeral[285].

Subsequently, a small-scale study in England by Abrahams (2009) found that initial 'absolute' enjoyment and excitement about doing practical inquiry wanes as students progress through their (11 – 16) secondary education. Following earlier studies, he found that interest became increasingly situational, as students reported liking practical work relative to other methods of teaching science (especially because they perceived it to be less boring than writing, or even as 'entertainment'[286]). This finding was confirmed more recently in a larger study[287].

Nonetheless, the 2019 iteration of the Wellcome Trust's Science Education Tracker, a nationally representative survey in England of early-to-late secondary school students' experiences and views of science and their science career aspirations, recorded that "practical work is key to motivating students in science, especially among students from economically disadvantaged backgrounds and those least engaged", and found that a lack of practical work deters students from studying science[288].

Recently, Dam *et al*. (2019) compared the situational interest among learners studying cellular respiration (a particularly challenging topic for students) using a conventional static flow diagram and pen–paper tasks with another group of students who performed a simulation using a concrete dynamic model made of Lego. These researchers found that while both groups considered the topic very important and meaningful, those in the experimental group showed greater enjoyment and were more excited by the materials they were using to explore it[289].

However, not all research has shown that engaging in practical inquiry increases situational interest. Holstermann *et al*. (2010) found that upper secondary students in Germany with experience of a range of hands-on biology experiments did not necessarily show greater interest in them than students who had no previous such experience. They found that the type of practical had a strong influence on the degree of interest shown. These findings indicate that situational interest is contingent on the type of activity; and that the speed with which it diminishes depends on students' perception of how engrossing an activity is[290].

3.4.2 Personal interest

Personal interest refers to an enduring interest in something, which may develop from repeated experiences of situational interest (such as engaging in practical inquiry) if this is perceived by students as having personal relevance and meaningful to them[291, 292, 293, 294]. Hutchinson *et al*. (2011) found that middle and high school students were more interested in a practical inquiry activity if they felt it had relevance to them[295] and Hulleman & Harackiewicz (2009) observed that students' interest and performance were impacted according to whether they perceived a topic as being relevant to them[296]. Similar effects were discernible in an evaluation of the Salters' Advanced Chemistry course, with the relevance of the course content being credited with increased aspirations to study chemistry at university[297].

However, it is more common that references to the effect of practical inquiry on 'interest' are not prefixed by 'situational' or 'personal'. This is understandable when data from students are being collected, partly because students need to be asked about their experiences in language they will understand and partly because their responses may be hard to categorise. For instance, in England, a small-scale study of 13 – 15 year old students used various materials to produce different colours in a Bunsen burner flame and were required to identify them. Toplis (2012) discusses whether the following response should be understood as 'situational interest' or 'motivation'[298]:

"Erm, 'cause it was interesting to see, like the reactions but then it was still educational because we had to try and figure out which ones they were but it was good for us all to do it."

Toplis argues that: “This piece of practical work has managed to capture a degree of interest, that of finding out some unknown. As such, it appears to go beyond the situational interest or even an episode that is remembered as a task that has been done. The requirement to ‘figure out’ would suggest an intrinsic interest with a need or desire to find out. As such there is a goal and it could be argued that there is a motive here. The feature here is that with the flame tests practical, there are unknowns and these may have provided motivation as there is a problem to solve, which in itself is a goal. However, although this goal may or may not endure, the student is curious about the need to solve a problem, and aware that there is an approach to doing so”.

3.4.3 Impact of practical inquiry on students’ motivation

Motivation has been defined variously as “any process that initiates and maintains learning behavior”, without which no learning is possible[299] or “the manifestation of an individual’s ‘inner drive’, which derives from personal interest”[300].

Motivation and engagement are essential if people wish to learn[301] and both are affected by the nature of instruction. While, due to individuals’ uniqueness, there is no singular pedagogy that is assured to motivate, investigations into the impact of practical inquiry on motivation are often based on observing and recording students’ responses to actively engaging in inquiry-based approaches.

Crucially, researchers have found that students are more likely to be engaged and motivated to learn, and perform better, if they can strongly identify with the scientific content, ie if it is relevant to their lives[302, 303, 304, 305, 306] particularly so if they are not considered to be high attaining[307]. Further, this sort of experience is best achieved through project-based learning activities in which students apply their scientific knowledge and skills to addressing ‘real world’ problems, often with the support of each other, their teachers and, sometimes also, professional scientists[308, 309, 310, 311, 312].

In their study, Rahayu *et al*. (2011) looked at the effect of different teaching approaches on engaging grade 11 (16 – 17 year old) Indonesian students. They found that a practical-inquiry-centred and collaborative approach to learning about acids and bases, using ‘real world’ contexts, was more effective than teaching the same content using ‘traditional’ teaching methods. The combination of enjoyment and increased self-efficacy associated with the former approach, together with positive outcome expectations, enhanced the students’ motivation[313]. Others have found a similar beneficial impact on motivation through participation in practical inquiry activities compared with traditional teaching methods[314].

In another context, provisioning accessible hands-on experiments in mobile science laboratories (‘laboratories on wheels’) has been credited with stimulating and increasing the motivation of rural students in Turkey who would otherwise not have opportunities to access high-quality science education[315].

3.5 Impact of practical inquiry on students' attitudes to science and to learning and studying science

As has been suggested above, attitude towards science develops from a combination of cognitive and affective factors that inform students' personal beliefs and their collective response to their experiences of science education (including the cognitive processes involved in undertaking practical inquiry)[316].

Students are likely to have an overall positive attitude to practical inquiry if their affective, cognitive and behavioural responses (Table 5) are themselves all positive, and the opposite also holds true.

In the sense that attitudinal development is culminative, it is understandably considered to be of especial importance in comprehending the subject and career choices students make (see Chapter 6). However, many research studies focus on identifying shifts in attitude detected through questionnaires and/or interviews as a result of a particular intervention, and the lack of follow-up means that it is not possible to be certain as to whether any (positive) changes detected endure or are merely fleeting responses to a novel experience (and, at best, indicative of apparent shifts in attitude). That said, just as repeated stimulating experiences of practical inquiry (situational interest) may ignite a passion for science (personal interest), it seems reasonable to conjecture that the same could apply to attitudinal development.

Consequently, when single intervention studies claim to have detected changes in students' attitudes, it may be that they are really relating a situational interest response. Nonetheless, studies identified by the research protocol underpinning this report have found that practical inquiry activity can enhance students' positive attitude towards learning science[318, 319, 320]. Notably, in their analysis of data relating to 4,456 US students who had participated in the OECD's PISA 2006 tests, Grabau & Ma (2017) report a positive relationship between participation in hands-on science activities and their 'general interest in science' rather than any more permanent change in students' 'attitude', though many of the references they cite mention 'attitude' in their titles[321].

TABLE 5

Components that together help form attitudes[317]

	Response category		
Response mode	**Cognition**	**Affect**	**Conation**
Verbal	Expressions of beliefs about attitude object	Expressions of feelings toward attitude object	Expressions of behavioural intentions
Nonverbal	Perceptual reactions to attitude object	Physiological reactions to attitude object	Overt behaviours with respect to attitude object

The following subsections focus on studies that have a longitudinal component that reliably may be associated with attitudes.

3.5.1 Attitudes towards practical inquiry vary across the sciences

Although most research reviewed for this report focused on practical inquiry in science in general, or on students' attitudinal responses to practical inquiry in particular aspects of the physical or biological sciences, researchers have recently found that between Year 7 (ages 11 – 12) and Year 10 (ages 14 – 15), attitudes to practical inquiry decline faster in physics than they do in chemistry or biology[322].

3.5.2 Declining attitudes to the sciences during secondary schooling

In England, regardless (or perhaps because) of significant changes that have been made to the science curriculum over the past 20 years or more, studies have consistently documented that students' attitudes to science decline as they progress through their secondary education[323, 324, 325, 326] even though nationally representative student sampling indicates that 14 – 18 year olds enjoy practical inquiry[327]. Most recently, it has been suggested that this decline reflects a shift from enjoyment (the affective domain) to a focus on preparation for public examinations (the cognitive domain)[328], a negative reflection of a system that ultimately values evidence of knowledge gain more highly than individuals' learning and development (eg in respect of reasoning ability, critical thinking and wider skills, discussed in Chapters 4 and 5).

3.6 The impact of digital technologies

Digital technologies have become increasingly sophisticated over recent decades, and just as their usage in schools has become more widespread, so interest in assessing their efficacy has grown.

Lowe *et al*. (2012) reported that the results of some 400 peer-reviewed publications on the use of remote laboratories[viii] published in the previous decade were 'somewhat mixed', although these were predominantly focused on undergraduate learning. These authors found from their study of 112 secondary school students' experiences of working with a remote laboratory that 64% agreed that it was 'reasonably fun' or 'a lot of fun' although only 7% agreed with the statement "I prefer remote labs to hands-on labs"[329].

In addition, the past 15 years or so have witnessed an increase in the number of studies assessing the effects and effectiveness of 'virtual laboratories'[ix] in engaging students, often in comparison with conventional practical inquiry activities. (Virtual laboratories are widely used in America[330].) Such studies have focused on lower or upper secondary students, or sometimes both, and have covered a range of topics in biological and physical sciences curricula. They often report that virtual laboratories have positive effects on students' engagement in practical inquiry activities (as well as their knowledge and skills; see Chapters 2 and 4 in this report) and some studies find that these positive effects are as strong or stronger in virtual formats compared with physical laboratory or field environments[331, 332, 333].

[viii] These authors state that remote laboratories 'allow students and teachers to use high-speed networks, coupled with cameras, sensors, and controllers, to carry out experiments on real physical laboratory apparatus that is located remotely from the student'.

[ix] Virtual laboratories are simulated learning environments that allow students to conduct laboratory experiments online and explore scientific concepts and theories.

But, interestingly, some studies have shown that experience gained in a virtual laboratory may not only increase students' engagement, but also boost their self-confidence when working in a physical laboratory[334].

3.6.1 Digital technologies outside school

Nugent *et al*. (2010) found that extracurricular science enrichment activities of varying length using robotics and geospatial technologies had a positive effect on middle school students' self-efficacy and general attitudes towards science. They assert that such intensive experiences (during a summer camp) provide opportunities for students to engage more deeply in STEM concepts than would normally be possible in more formal conventional educational settings; and that such activities have the potential to encourage students to explore these subjects further and improve their STEM learning[335].

3.7 Conclusions

There is a perceived conventional wisdom conveyed summarily in 'grey' literature that participation in high-quality practical inquiry stimulates students and heightens their personal interest in science[336, 337]. This evidence synthesis confirms that there is a substantial body of evidence showing that engaging in practical inquiry activities may have a short-lived stimulatory effect on interest, but that repeated practical inquiry experiences are likely to be required to kindle a lasting interest in science. However, personal interest should not be conflated with attitude, which is a longer-term effect influenced by many factors, of which practical inquiry is one. Research suggests that the decline in attitudes towards science that develops early in secondary education may be linked to reduced enjoyment of practical inquiry resulting from a progressive focus on preparation for public examinations and a focus on developing lower-order skills (such as memorising and recalling knowledge).

3.8 Limitations

It is important to point out that terms such as 'interest', 'enjoyment', 'attitude' and 'motivation' are often used interchangeably within the literature as though they are synonymous[338]. This can make it hard to discern what is being measured and how terms relate to one another.

The research literature does not cover each of these aspects of affect evenly and the meaning ascribed to each is not consistent, and often ambiguous. In their significant review, Osborne *et al*. (2003) state that "the concept of an attitude towards science is somewhat nebulous, often poorly articulated and not well understood"[339], and this generally remains the case.

However, a few researchers are much more precise and rigorous in defining what they mean by one or other of these terms. This variability is neatly summarised by Potvin & Hasni (2014) in their systematic review of research on students' interest, motivation and attitudes towards science and technology, including a number of studies concerned with 'hands-on' science. These researchers found that 39 out of 63 papers (62%) referring to 'interest' used the term "without explicitly providing a definition", that 20 out of 49 papers (41%) concerned mainly with 'motivation' failed to define the term explicitly, and that 71 out of 121 papers (59%) focused on 'attitude' did not explicitly define this term[340].

The rationale for using one term as opposed to another is not necessarily clear. In 2006, the OECD adopted ‘science engagement’ as an umbrella term covering “self-related cognitions, motivational preferences, emotional factors as well as behaviour-related variables (such as participation in science-related activities in and out of school)”[341].

The distinctions between these terms are important. For instance, expression of enjoyment may not necessarily increase motivation to study, learn or change attitudes. Notably, Toplis (2012) highlights that where students report positive impacts of engaging in practical inquiry, such as “a sense of fun, personal relevance, personal involvement, motivation and the opportunity of working together that raised interest … there is a need to look to some possible reasons behind the use of these words or ideas [and] discuss how or where this interest arises and why practical work provides it”[342].

Similar problems have been detected in teachers involved in research into the effects of practical work. Abrahams (2009) observes that “the term ‘motivate’ was frequently used by science teachers within this study to describe the value of practical work” prompting him to ask: “Are teachers, we might then ask, using this term in its strict psychological sense or as a “catch-all” term that embodies elements of interest, fun, enjoyment, and engagement?”[343]

Measurement of affective responses relies on teachers’ perceptions or students’ answers to questionnaires normally collected immediately following an activity. Potvin & Hasni (2014) are highly critical of the diversity of questionnaires that researchers have deployed to measure students’ reactions to an intervention:

“As for the questionnaires that the articles have described and used for research, we can only regret the very large number of them that were used or developed. After examining most of them, we conclude that they are often quite redundant, and in many cases the reason why new tools have been proposed and validated eludes us. Many questionnaires ask essentially the same questions, but in forms that are dimly divergent, so that they pursue the same goals, while simultaneously forbidding comparisons from one article to the next.… [So] … researchers [should] consider using items or instruments that are already available … thus allowing interesting comparisons between student profiles, countries, interventions, durations, etc”[344]. Regardless of which instruments are used, they must have validity.

Such measurements are also snapshots in time. Since studies tend to focus on the immediate response to an intervention, there is no way of knowing whether these data have longer-term significance with respect to students’ progress, or their subject and eventual career choices (see also Chapter 6). As Bennett (2003) has observed, “with all research into attitudes, there is the problem of the extent to which actual behaviour is linked to declared attitude behaviour”[345].

Impact of practical inquiry on students' development of scientific and wider skills

4.1 Skills are an integral part of practical inquiry

Teaching skills should be a fundamental part of education. Debates that pitch knowledge against skills, framing them as two diametrically opposed forms of cognition, give a narrow and reductive view of teaching and learning. Skills are a type of knowledge. They represent the difference between knowing what and knowing how. Knowledge and skills should instead be considered complementary.

The teaching of skills is one of the core justifications of practical inquiry by teachers (Table 6) and the most emphasised purpose of practical inquiry in many of the world's highest performing education systems such as Singapore, Japan and Canada[346]. Several skills are listed in England's national curriculum for science[347] and within the Northern Ireland curriculum, even more focus is put on the development of whole curriculum as well as science-specific skills[348, 349].

Some skills are taught because they are integral to understanding the scientific process. Other skills may have value in a broader context. A wide range of skills needs to be taught as part of a broad and balanced education[350].

TABLE 6

Teachers' justification for practical inquiry[351]

	Open respondents % (*n*=30)
Teach skills	70
Motivate pupils	60
Understand investigation processes	47
Encourage enquiry	37
Teach concepts	37
Provide pupil enjoyment	33
Show how science works	23
Link practical to theory	23
Provide science contexts	20
Encourage creativity	13
Encourage group work	7

4.2 A broad range of skills can be taught

The word ‘skills’ has been used in the context of practical inquiry in a variety of different ways[352]. More than 100 references to various types of skills, level of skill and skill complexity were identified in the process of conducting this evidence synthesis. Some of the skills mentioned are particularly associated with practical inquiry (eg ‘experimental skills’, ‘fieldwork skills’, ‘hypothesising’, ‘manipulative skills’, ‘measurement’, ‘modelling skills’, ‘observation skills’, ‘scientific explanation construction skills’) while other skills highlighted might be construed as being more generic (such as ‘communication skills’, ‘cognitive skills’, ‘collaboration skills’, ‘problem-solving skills’). Terms used to describe skills (such as ‘basic skills’, ‘higher-level skills’ and ‘higher-order skills’) were rarely clearly explained or defined in the literature, leaving too much to interpretation. Skills are rarely practised discretely, and one activity will likely involve a variety of skills. Furthermore, the development of skills in one area may influence learning in a seemingly quite different domain. For example, cooperative learning can have a positive influence on the development of graphing skills[353].

There is also no simple, singular, way to group these skills. Skills identified by Bloom’s taxonomy have subsequently been categorised as ‘lower-order’ or ‘higher-order’ according to their cognitive demand[354]. In a practical inquiry context, ‘lower-order’ skills (remembering, understanding, and application) may involve students successfully following instructions and carrying out a ‘recipe’ style practical. Higher-order skills include analysis, evaluation and synthesis and will develop students’ critical thinking and problem-solving skills. In the context of practical inquiry, these skills are developed when students draw conclusions from their data, design and evaluate experiments or tackle open-ended problems.

The OECD Learning Compass 2030 categorises three different types of skills[355]:

- practical and physical skills, which include making careful measurements and observations, carrying out procedures and using new information and communication technology devices.
- cognitive and meta-cognitive skills, which include critical thinking, creative thinking, learning-to-learn and self-regulation.
- social and emotional skills, which include empathy, self-efficacy, responsibility and collaboration.

Some examples have been collated below to demonstrate the breadth of skills that can be taught in practical inquiry lessons and how they could be grouped. These are meant to be illustrative rather than definitive, and in reality it would be difficult to fit skills into such neat divisions.

4.2.1 Hands-on vs minds-on skills

Hands-on skills actively engage students in science[356, 357] and are associated with doing ‘real’ science[358]. Generally, these skills involve the physical manipulation of objects, eg the use and safe handling of scientific equipment (such as a Bunsen burner or microscope) and interaction with materials (eg chemicals). Crucially, while participation in hands-on activities is more valuable than passive pedagogical practices (such as reading a textbook)[359], this is insufficient on its own to change students’ conceptual grasp and requires reflection and class discussion of their experiences[360, 361, 362]; see Chapter 2). In contrast, minds-on skills are cognitive, concerning the acquisition of knowledge and conceptual understanding (eg analysing, synthesising, classifying).

4.2.2 Process skills vs practical skills

Process skills such as predicting, observing and inferring, relate to ways of thinking about and interacting with materials and phenomena. These lead to an understanding of scientific ideas and concepts that allow students to think scientifically by involving the means and methods used to obtain scientific information[363]. Practical skills are those needed to carry out a task, eg using new information technology devices, performing a titration or reading an oscilloscope.

4.2.3 Science-specific vs general skills

Science specific skills are required for practising science and will be needed by future scientists, eg hypothesis creation and development, CVS (control-of-variables strategy) skills, completion of procedures and careful recording of data, and making accurate observations and measurements. In England, even though these experimental skills are listed as part of the national curriculum, university science departments report that many first-year undergraduate students lack basic laboratory skills[364].

General skills are integral to practical inquiry but have wider applicability to other areas of life and could also be called employability skills. These skills are described within the Skills Builder Universal Framework and include time management, problem solving, teamwork and collaboration (Figure 9[x]).

FIGURE 9

Skills Builder's Universal Framework for essential skills[365]

Source: Skills Builder Partnership.

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x. The Skills Builder Universal Framework is a toolkit to help children and young people develop essential transferable skills for employment. It has been developed by the Essential Skills Taskforce: CIPD, CBI, Gatsby Foundation, EY Foundation, Careers & Enterprise Company, Business in the Community, and the Skills Builder Partnership.

4.3 Assessing practical inquiry skills

Accurately monitoring and assessing practical inquiry skills is difficult. This is partially due to the range of skills associated with practical inquiry, and the trouble with identifying, categorising and assessing them.

The main areas of debate include: the range and nature of skills to be assessed, the balance between the assessment of prescriptive or investigative tasks, and the extent to which the assessment should be holistic, or atomistic, in its approach.

It has long been recognised that assessment drives what is taught in schools to a considerable extent. If practical work is not assessed at all, its provision would be put at risk[366]. Teachers' preferences for using different types of practical work are routinely influenced by their considerations of curriculum targets and methods of assessment[367].

To ensure reliability, teacher assessment requires robust approaches[368]. In practice, formal assessment of practical abilities has tended to be restricted to a limited number of aims: manipulative skills and techniques, accurate observation and description, and data collection, presentation and interpretation[369]. The pressure of high stakes assessment and qualifications means that teaching is more likely to focus on procedures and less likely to focus on developing higher-order thinking skills linked to creativity, evaluating and self-monitoring of learning[370].

Some skills are difficult to evaluate with traditional paper-and-pencil tests; therefore, these tests alone may be insufficient for monitoring and assessing how well students are developing scientific inquiry abilities[371]. Written tests can also create a mismatch between students' ability to design and carry out an investigation and their ability to produce a good report; in some cases, students can produce a good report because they know the rules of the game[372]. One study showed that students trained with paper-and-pencil tasks, outperformed students trained with hands-on tasks on paper-and-pencil assessments, but students trained with hands-on tasks would outperform students trained with paper-and-pencil tasks on hands-on assessments[373].

Skills can be assessed directly as students perform a skill, or indirectly where a student's competency is inferred from their data and/or reports of their work. There are advantages and disadvantages to each of these methods (Table 7) and they are in fact complementary.

Abrahams & Reiss (2015) recommended that direct assessment is more appropriate if the intention is to determine students' competency in terms of actual practical skills. If, conversely, the intention is to determine students' understanding of a skill or process, then indirect assessment is generally more appropriate[374]. They are not mutually exclusive and both would feature as part of a holistic science education.

TABLE 7

Comparison of direct assessment of practical skills (DAPS) with indirect assessment of practical skills (IAPS)[375]

	DAPS	IAPS
What is the principle of the assessment?	A student's competency at the manipulation of real objects is *directly* determined as they manifest a particular skill	A student's competency at the manipulation of real objects is *inferred* from their data and/or reports of the practical work they undertook
How is the assessment undertaken?	Observations of students as they undertake a piece of practical work	Marking of student reports written immediately after they undertook a piece of practical work *or* marking of a written examination paper subsequently taken by students
Advantages	High validity Encourages teachers to ensure that students gain expertise at the practical skills that will be assessed	More straightforward for those who are undertaking the assessment
Disadvantages	More costly Requires teachers or others to be trained to undertake the assessment and has greater moderation requirements	Lower validity Less likely to raise students' level of practical skills

4.4 Transferability

The transferability of skills to other areas of the curriculum, as well as to everyday problems, is often cited as a key reason to conduct practical inquiry[376, 377]. However, "a considerable body of psychological literature suggests that the notion of skills transfer is highly problematic"[378]. Indeed, there is limited evidence, in relation to practical inquiry, that manipulation of objects and observation of phenomena[379] develop students' transferable skills.

One factor that influences the transferability of a skill is the difference between the context in which training is given and the context of the application. This difference is presented on a continuum known as near/far transfer. 'Near transfer' occurs when the training and application are very similar and 'far transfer' is when they are more different[380]. The misalignment between instruction and assessment of skills can create challenges. Studies have found that in day-to-day teaching practice, hands-on learning experiences should be assessed with hands-on assessments, cautioning that such assessments are less likely to adequately measure student learning if they involve 'far transfer' tasks[381].

Transfer of skills is "unlikely to take place unless very clear links are made to pupils between one situation and another"[382]. As the Durham Commission on Creativity found, "it takes considerable practice to transfer skills from one domain to another"[383], but some studies suggest that appropriate scaffolding (such as laboratory guides and worked examples) can help improve the transferability of skills[384, 385, 386].

4.5 Teaching skills

If a specific skill is necessary for a task, students need to be competent in this beforehand, or it may impede the intended learning[387]. Otherwise, students are likely to focus on technical manipulative skills (such as correctly handling a burette) and be unable to engage with the scientific concepts and processes that are under investigation (such as the process of titration to establish the concentration of a substance).

Explicit (highly guided) instruction has been recognised as a particularly effective way of teaching factual information and specific skills[388] and teacher demonstrations may have a role to play here (although it is worth noting that some studies have shown that students prefer to be actively engaged in practical inquiry rather than passively watch a demonstration[389, 390]). However, an overreliance on explicit instruction or the overuse of 'recipe' style practical inquiry activities will limit students to practising 'lower-order' thinking and skills[391, 392].

If teachers want to develop students' procedural understanding[393], science process skills[394] and higher-level skills, such as problem solving, a more open form of inquiry is beneficial[395]. For this to be successful, students must already have pre-existing low-level skills (such as how to operate apparatus) and some relevant knowledge and conceptual understanding[396, 397].

4.6 Virtual laboratories

Emerging evidence suggests that virtual laboratories can aid skills acquisition[398]. There are obvious advantages to developing some skills virtually. Simulations can allow learners to practise skills in a safe environment before applying them to real life situations. Other activities, such as conducting dissection procedures, may not only be financially costly, but also inconsistent with students' personal beliefs[399].

One meta-analysis noted that use of virtual labs could also be effective for teaching science process skills[400] while another found that few papers examined their use in developing higher-order skills[401]. The advantages of using virtual laboratories in one domain could be at the expense of another (eg collaboration skills). However, more research is needed to properly determine which skills benefit most from this approach to teaching practical inquiry.

Technology may also be able to help with the assessment of some skills in the future. One small-scale study demonstrated how a digital learning environment could assess students' skills rigorously, frequently, and in the context in which they are developing. The programme can then use machine learning to assess and scaffold students' scientific inquiry skills[402].

4.7 Conclusions

Participation in practical inquiry can support the development of a broad range of physical (manipulative), process and cognitive skills (such as experimental design, making accurate observations and measurements) and a raft of wider skills, such as teamwork and communication, that have generic value, particularly in preparing students for employment. Students' understanding of a skill or their competency in it can be assessed directly or indirectly. There are strengths and weaknesses associated with each method of assessment.

4.8 Limitations

While it is challenging or even impossible to develop skills without practise, there is limited evidence available in the research literature concerning the extent to which young people develop practical inquiry skills.

There is currently a stronger evidence base around the impact of practical inquiry in improving physical skills and dexterity compared with other, intellectual, purposes of practical inquiry[403]. Meta-analyses found that hands-on activities had a significant positive effect on developing manipulation skills, but that such activities were less effective at increasing reasoning skills or developing conceptual knowledge and understanding[404].

There is a substantial body of evidence that suggests most students have difficulty using standard laboratory apparatus and carrying out standard laboratory procedures even after several years of studying science[405].

Impact of practical inquiry on students' understanding of the norms and values of science

5.1 Introduction

This chapter is concerned with research evidence covering the specific impact of practical inquiry on students' understanding of rules (norms) associated with good scientific practice (Table 8) and the common values that underpin them. These values may be epistemic (relating to the generation of knowledge) or non-epistemic (social values, political values, ethical values such as honesty, integrity, openness, open-mindedness, fairness, and accountability). Along with behaviours, expectations and attitudes, the norms and values of science contribute to the wider culture of scientific research and the efficacy of the science system.

Understanding how scientific knowledge is produced and the grounds for confidence in it, is vitally important, especially because scientific knowledge is not fixed (see the Introduction). This matters for everyday life and citizenship and the development of future professional scientists; from deciding whether to eat (un)pasteurised cheese, buy a hybrid car or receive a vaccine. Citizens need to understand the nature of scientific knowledge and practice to participate effectively in policy decisions and to interpret the meaning of new scientific claims[407]. They should be able to consider evidence and reach an informed conclusion, to be able to 'think like a scientist' and understand that scientific truth (or consensus) may change over time[408, 409].

TABLE 8

The norms of science[406]

Norm	Meaning
Universalism	All people, regardless of their race, nationality, religion, class and personal qualities, may contribute to the advancement of science
Communism	Science is a collaborative enterprise and the findings of science belong to all
Disinterestedness	Scientists should work for the benefit of humanity rather than for their own personal gain
Organised scepticism	Scientific findings should be subjected to objective, rational, scrutiny

5.2 Available evidence

There is little research examining how practical inquiry develops students' understanding of scientific norms and values and of their importance in research[410]. Studies are generally concerned with measuring improvement in the learning of scientific concepts[411], and the relationship between practical inquiry and students' understanding of scientific practice is underdeveloped. This is not surprising, considering the numerous different ways practical inquiry can be implemented and the complexities involved in teaching and assessing students' understandings of the norms and values of science.

The 2015 PISA study found that across OECD countries "more frequent enquiry-based teaching is positively related to students holding stronger epistemic beliefs"[412]. Other studies (for example, Smith *et al*. (2000)) have suggested that a constructivist approach to education (where students' knowledge is something to be built on rather than just passively taken in) and inquiry learning can promote science-related epistemic beliefs[413]. It has been asserted that experiences in the laboratory can help students develop ideas about the scientific community and the nature of science, encouraging the development of epistemological awareness and a better understanding of how scientific knowledge is created[414].

There is research on the importance of putting students in situations where they can experience the uncertainties of the real world and see how scientists deal with this[415]. Practical inquiry is an important tool for teaching about experimental design and can give students a 'feel' for the challenges of measurement, and an appreciation of the ubiquitous nature of uncertainty[416].

Indeed, the House of Commons Science and Technology Select Committee report on Practical experiments in school science lessons stated that:

"[Students] will need to understand how the knowledge and facts that they acquire in classroom lessons have been gathered and agreed. They cannot and should not do this exclusively second hand, through books without direct practical experience both in and out of the classroom"[417].

5.3 School science and professional science

A study exploring students' views of practical inquiry in England through in-depth interviews did not register 'working like a scientist' as a reason for doing practical inquiry[418]. Another study, conducted in America, found that while students' practices of inquiry initially appear to share much with scientific practice, their expressed epistemological beliefs can seem naïve by comparison[419]. Research has shown that inquiry tasks commonly used in schools evoke reasoning processes that are qualitatively different from the processes employed in actual scientific inquiry[420, 421]. In school, knowledge is often presented with an authoritarian and oversimplified narrative[422, 423] and experiments "typically show less variability[424] and additionally face time and resource limitations". Much of the complex, contested and interdisciplinary nature of professional scientific practice can be lost.

Textbook inquiry and 'recipe' style practical inquiry rarely, if ever, get students to think about alternative interpretations of the data generated or how to relate partially conflicting data to theory. Nor do these approaches encourage students to critically evaluate the methodologies they are following or the rationale for these[425]. Many of the 'recipe' style activities outlined for students in laboratory guides offer lists of tasks that students are expected to follow formulaically. This encourages low-level, linear reasoning, as students draw obvious inquiry-based conclusions from simple experiments and simple observations. Such activities do little to engage students in thinking about the wider purposes of their investigation and what needs to be done to achieve those ends[426].

One study in New Zealand found that while practical inquiry produced purposeful and focused learning, students acquired a narrow view of scientific inquiry, where thinking was characteristically rote and low-level. The nature of this learning was strongly influenced by curriculum decisions made by classroom teachers and science departments in response to the assessment requirements of a high-stakes national qualification. Students' learning about experimental design was reduced to an exercise in 'following the rules' as they engaged in closed rather than open investigations. Consequently, the resulting student learning was mechanistic and superficial rather than creative and critical[427].

By contrast, a study in Nigeria found that practical inquiry developed 'scientific attitudes' among students, defined as (i) curiosity (ii) open mindedness (iii) objectivity (iv) intellectual honesty (v) rationality (vi) willingness to suspend judgment (vii) humility and (viii) reverence for life[428].

5.4 Teaching about the scientific process

Over the past 60 years, major educational policy organisations from across the world have emphasised that students learn by engaging in the thinking processes and activities of scientists[429]. How students learn shapes what they learn. It is important for the focus of learning to extend beyond the acquisition of scientific concepts to how to hold claims accountable and to understanding how scientists collaborate to solve problems[430].

Learning collaboratively has been shown to help students learn how to deal with 'confusion and discomfort' and the "challenges encountered when working with others"[431] and it can also change their perceptions of science and their understanding of the nature of an expert scientific community[432]. Further, Chinn & Malhotra (2002) have asserted that if students are to gain appreciation of authentic scientific inquiry, then they need to be exposed not only to hands-on tasks, but also to database analysis, evidence evaluation, verbal design of research studies, and computer simulated experimentation[433].

Students need support from teachers to reflect on the investigative process, and on the nature of the knowledge produced, in students' own investigations and in the work of professional scientists. If students are given sufficient time for reflection and connect their experiments with what they have learned earlier, and if teachers find meaningful ways of assessing their students' laboratory work, practical inquiry can motivate students and improve their understanding of the nature of science[434, 435].

Kremer *et al.*'s (2014) study of biology education in Germany found evidence for the long-term influence of instruction on nature of science beliefs: students' understanding of the nature of science grew more sophisticated as they got older. Furthermore, while the nature of science beliefs did contribute to the formation of biological inquiry skills, inquiry activities did not easily change beliefs about the nature of science. These researchers concluded that biological inquiry processes can help to develop understanding of the nature of science, but that students need explicit instructional support to achieve this[436].

5.5 Teaching about the scientific enterprise

Teaching about contemporary or 'cutting edge' science is important, but it can often be difficult for students to understand the issues at stake sufficiently or the evidence supporting or challenging different viewpoints. Effective scaffolding is important for helping students learn the complex reasoning needed to succeed at complex inquiry (see Chapter 2). The inclusion of some history of science would be beneficial in teaching how theories develop and change[437].

The Gatsby Charitable Foundation makes a number of recommendations in its *Good Career Guidance* report for helping students gain an accurate impression of what being a professional scientist is like[438]. It is difficult for even the best-informed careers specialist, let alone the regular classroom teacher, to be aware of the latest developments in the labour market and career pathways or to provide real-world examples of what scientists actually do[439].

5.6 Independent research projects

Independent research projects (IRPs) (described in Box 1, Chapter 2) can have a positive impact on students' understanding of the norms and values of science.

One study showed that students participating in IRPs had an increased ability to generate hypotheses, consider alternative hypotheses, implement models and logical argumentation in explanations, connect ideas, extend concepts and ask questions[440]. This suggests that meaningfully engaging students in real science can make a difference to their understanding of how science works.

One of the benchmarks in the Gatsby Charitable Foundation's *Good practical science* report is for students to carry out open-ended investigative projects. A key reason for this is to give students experience of what it is like to do 'real' scientific research and thereby learn how science is done and what it is like to be a scientist. This is a common view expressed by students who conduct IRPs[441, 442]. Students also noted that through their IRP they had been involved in a communal experience that they described as being more in line with real science, noting that scientists tend to work in research groups rather than in the individualised way they are used to working in school[443]. The Nuffield Foundation (2013), reporting on the Nuffield Research Placements scheme, found that placement students acquire a much better understanding of what it means to be a scientist, and a much better knowledge of the range of jobs in which scientists engage[444].

5.7 Conclusions

Practical inquiry can have a positive effect on developing students' understanding of professional science practice. However, 'recipe' style forms of practical inquiry are not nearly as effective as open-ended forms of practical inquiry in which students take a measure of control over their own learning. Activities that are 'authentic' in nature give students a better understanding of the scientific process, including the challenges of experimental design and measurement, and greater appreciation of uncertainty in science.

5.8 Limitations

5.8.1 Depth of research

There is little research that specifically focuses on how practical inquiry can influence students' understanding of the norms and values of science. Initial screening identified studies focusing on undergraduate students, and teachers' understanding of science (especially in teachers of younger age groups who are less likely to have a science degree), but these fall outside the scope of this evidence synthesis and have not been reviewed.

5.8.2 Semantics and definitions

There is a lack of clarity about the terms researchers use. For example, when research studies discuss understanding of science it is sometimes unclear as to whether they are referring to understanding of the content, the process, the enterprise or the profession. Further, there is no universal set of values that scientists ascribe to, be these epistemic (linked to the generation of knowledge) or non-epistemic (social, political and ethical values)[445]. This makes teaching these values to students difficult and researching this in education challenging.

5.8.3 Methodological difficulties

In addition to the problems created by not having shared terminology, other methodological issues mentioned previously (see Limitations, Chapter 2) apply here too, particularly that studies are usually quite small-scale, short term, and lack a standardised method of assessment.

Some studies show that students' understanding of science becomes more sophisticated as they get older, but a lack of high-quality longitudinal studies means it is not possible to gauge the relationship between this and practical inquiry, and the impact of different teaching methods or interventions.

Studies on IRPs tend to overly rely on student surveys as the sole method of data collection and they rarely use some form of control. It has also been noted that more needs to be done when evaluating IRPs to gather data on students' views of the nature of science[446].

Impact of practical inquiry on students' progression and career aspirations in science

6.1 Introduction

This chapter examines the impact of practical inquiry on progression and career aspirations in science. To understand how practical inquiry may impact these, the chapter first considers the factors thought to be most important in influencing students to choose certain subjects and careers. It then reviews the evidence as to how practical inquiry might impact these factors, considering different types of practical inquiry and experiences.

6.2 Reasons for increasing science progression and career aspirations

The Science and Technology sectors are set to play a key role in strengthening economies, reflecting the fact that many countries have an increasing demand for STEM expertise[447]. Practical inquiry is part of science and needs to be learnt for its own sake. It is also an 'authentic' way to learn science, reflecting the research and practice that real scientists 'do'[448, 449]. Effective practical inquiry enables and encourages students to develop and use skills that are essential for many STEM careers such as data collection and analysis, critical thinking, communication, collaboration and teamwork[450].

Some groups are currently underrepresented among students who choose to study science post-16. Research in the UK has shown that these include women, certain ethnic minorities, and people from low socio-economic backgrounds[451]. Increasing the diversity of students with scientific career aspirations would ensure that the very best talent is available for future science jobs. In England, a recent All-Party Parliamentary Group (APPG) report suggested that practical inquiry in schools should play a role in improving the equity of science education[452]. Not all students have access to frequent and high-quality practical inquiry experiences in school, and those with the least access tend to be those from underrepresented groups and/or students with less 'science capital'[453, 454, 455]. There is evidence to suggest that participation in practical inquiry can be key to motivating students from socially disadvantaged backgrounds. These students may suffer most from a progressive reduction in practical inquiry opportunities during the early years of secondary education, making it less likely that they will end up pursuing scientific careers[456].

6.3 Factors that influence progression and career aspirations

Many factors influence students' choices in terms of further study and careers. These can generally be grouped into factors associated with individuals, such as their interest, confidence and ability in science, which will be informed to an extent by the school environment, factors within the school such as the availability and quality of well-resourced science laboratories and expert teachers and technicians, and external factors, such as family and societal expectations and pressures[457, 458]. In addition, assessment systems[459] and even geography[460] can also influence progression in different subjects.

Science self-efficacy, relating a student's perceived ability, achievement, and confidence in science, is an important internal factor determining student choice. Students with higher science self-efficacy are more likely to have positive perceptions of science, and more likely to aspire to a career in science[461, 462, 463].

Outcome expectation, meaning what a student expects to gain from studying science and/or a career in science, in terms of skills, opportunities, and prospects, is another important internal factor for student choice[464]. Unsurprisingly, students who choose science courses are more likely to agree that science graduates have wide career choices and prospects[465].

There are also other internal factors which have an impact student choice in their progression and careers. These factors include science attainment, motivation and enjoyment (see Chapters 2 and 3).

6.4 The impact of practical inquiry on progression and careers

Learning experiences such as practical inquiry can typically only impact internal factors determining students' progression and career choices[466]. This means learning experiences usually have an indirect impact on whether students choose to study science and to pursue a scientific career[467, 468].

For example, a survey of almost 3,000 15 – 16 year old students in Finland found that direct correlations between teaching practices such as practical inquiry and intent to enrol in further physics study were much weaker than the correlations with other factors such as belief in ability, enjoyment and perceived importance of physics[469].

Instead, learning experiences such as practical inquiry influence students' confidence in and their perception of science, which can then impact their progression in science and their career aspirations[470, 471, 472] provided these experiences relate to everyday life and what it means to 'be' a scientist[473]. Further, the impacts of learning experiences on individuals are likely to be small relative to the many other impacts on internal and external factors determining student choice (see also section 6.6). That said, the frequency with which students experience practical inquiry is also likely to affect their motivation to pursue a scientific career. This is precisely what was found in England (pre-Covid-19), where young people have reported a progressive and dramatic decrease in fortnightly opportunities to participate in hands-on practical inquiry during their secondary education and, associated with this, similar falls in their self-reported interest in learning science (Figure 10a) and desire to have a career in science (Figure 10b)[474].

There are different types and styles of practical inquiry that students may experience during their scientific studies. The next few sections evaluate the current evidence for how each of these kinds of experiences can impact progression and career aspirations.

FIGURE 10a

Proportion of Years 7 – 11 who participate in hands-on practical inquiry activity at least once a fortnight by school year; proportion in Years 7 – 11 who cite enjoying practical work as an incentive to learn science by school year (2019)[475]

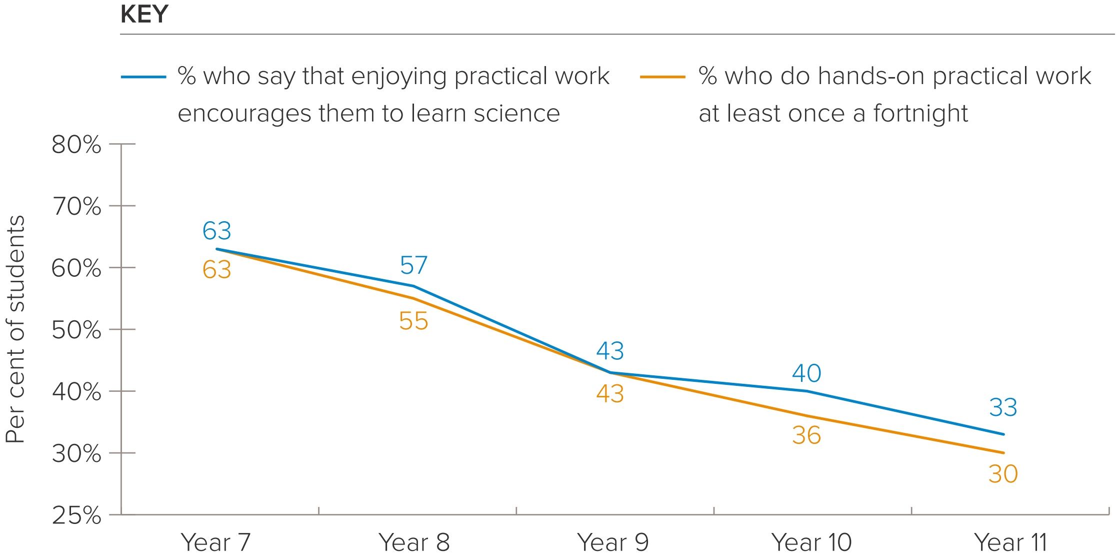
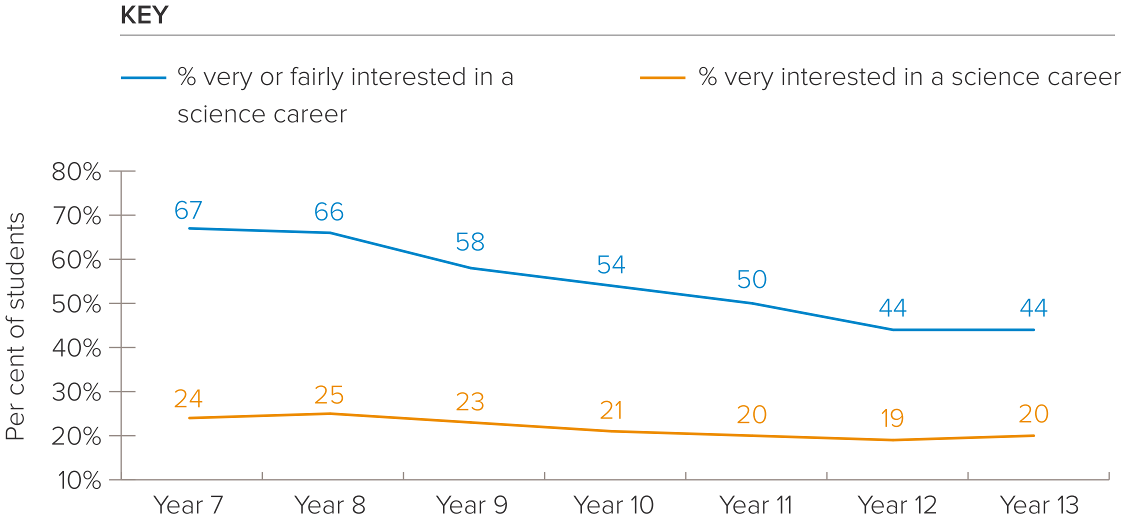


FIGURE 10b

Level of interest in a science career by school year (2019)[476]



6.4.1 Regular practical inquiry in classrooms

Anecdotally, many scientists would agree that participating in practical inquiry at school was an important factor that encouraged them to pursue science[477]. However, there are relatively few studies which explicitly consider the impact of practical science in classrooms on progression and career aspirations.

The OECD's report of the PISA 2015 tests included an analysis of how different factors correlated with students' expectation of whether they will be working in science when aged 30. The analysis found that time spent learning science was one of the factors that correlated most strongly with science career aspirations (Figure 11). This positive correlation was significant for both time in the classroom and time after school. Other factors that were significantly positively correlated with career aspirations included how well equipped the students' science department was and whether the school offered science competitions.

The PISA 2015 report did not explicitly look at practical inquiry, but instead considered the frequency of a range of teaching approaches such as enquiry-based, teacher-directed and adaptive instruction. All teaching methods considered had a similar positive correlation with career aspirations once attainment and the socio-economic profile of students were controlled for (Figure 11).

An analysis of PISA 2006 data found that students exposed to more inquiry-based science, of which practical inquiry is an important aspect, were more likely to agree that they would like to study science after secondary school[479]. Similarly, further analysis using PISA 2015 data from Finland found that students were more likely to be interested in a science career when inquiry activities, such as conducting a practical experiment or drawing conclusions from data, were offered in schools[480].

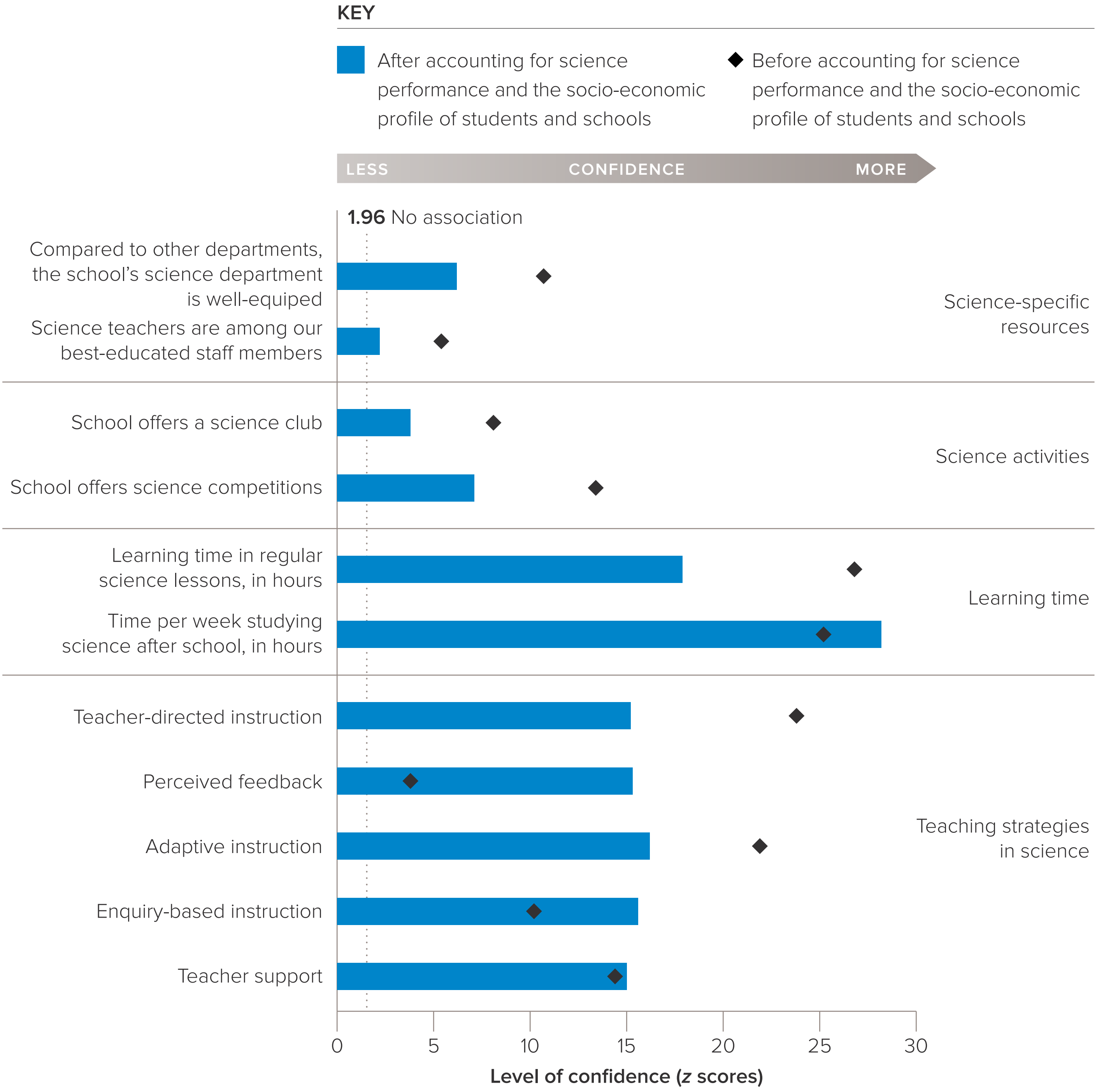
Analysis of the Salters' A level Chemistry course considered its impact on progression to further study of chemistry[481, 482]. This course aims to teach chemistry via context-based learning, to demonstrate the relevance of chemistry to students' everyday lives. Each practical experience is designed with this in mind. The course also includes an extended practical project, which gives students considerable freedom in terms of what they choose and how they conduct the work, with input provided by the teacher at all stages.

Case study and survey data of teachers suggests that students who take the Salters' course are more likely to study chemistry at university and aspire to pursue chemistry-related careers, compared to those taking a more traditional chemistry course[483, 484].

Combined with the above, several other studies have indicated that inquiry-based experiences in classrooms, including practical inquiry, can have a positive impact on interest and intent to progress further with science study and careers[485, 486].

FIGURE 11

Relationship between aspects of science education and students' career aspirations[478]



Notes:
1. The socio-economic profile is measured by the PISA index of economic, social and cultural status.
2. Time spent learning in addition to the required school schedule, including homework, additional instruction and private study.
3. All differences are statistically significant.
4. *Z* scores measure the confidence that an association exists between explanatory variables and students' expectations of working in a science-related career. *Z* scores above 1.96 mean that the relationship is statistically significant at the 95% confidence level.
5. Source: OECD, PISA 2015 Database, table II.2.30.

6.4.2 Enrichment and extracurricular activities

Activities taking place outside of the traditional classroom experience can have a positive impact on science progression and careers.

A study of 1,076 secondary school students in Singapore compared the attitudes of students who chose to study physics at university with those who chose another subject, including other sciences and non-science subjects[487]. All students agreed that they valued laboratory work in helping them learn physics and reinforced what they learnt in class. However, students who chose to continue to study physics were more likely to agree that enrichment activities such as collaborations between their school and scientists, and attending visits and talks, helped in their learning of physics.

In agreement with this, a retrospective survey of college students in the United States found that extracurricular activities were the most influential type of experience for igniting their interest in STEM, compared to classroom experiences and hands-on projects[488]. However, the authors were clear that this finding should not be used to minimise the importance of hands-on experiences in classrooms.

More recently, Allen *et al*. (2019) analysed the effects of 158 STEM-focused after-school programmes in the United States on nearly 1,600 students aged 10 – 18 and found, based on their self-reported experiences, that these activities had increased their interest in pursuing careers in STEM[489].

In the UK, the Royal Society's Partnership Grants scheme is an example of an extracurricular experience, organised by schools or colleges in partnership with a local scientist, industrial partner or science organisation. A recent independent evaluation of the scheme found that almost 50% of surveyed teachers agreed that more students had chosen to consider pursuing a STEM career as a result of their participation in the scheme. None of the teachers surveyed felt fewer students had chosen to study science further after taking part in the scheme, but the majority said they did not know or that it would be impossible to tell, particularly those who were teaching primary school students.

Similarly, the Institute for Research in Schools (IRIS) ran online enrichment projects for students during the Covid-19 pandemic, designed to give them insights into science by allowing them to participate in research. A survey of students participating in these projects found that 81% said the IRIS projects had made them excited about science during lockdown, and three in five felt that the projects had improved their awareness of future career opportunities[490].

Enrichment and extracurricular activities can provide students with valuable insights into how science works, what science careers involve, and spark excitement and interest in science. The evidence suggests these activities are particularly effective in increasing progression and career aspirations when they demonstrate the relevance of science to students' everyday lives[491].

6.5 Project-based learning

Practical inquiry projects in science can happen inside or outside the classroom (including in STEM workplaces). Studies of these involve students focusing on a topic for multiple hours or lessons. Most studies suggest that participating in these projects helps students develop skills such as hypothesis testing and problem solving.

Projects can make up a style of tuition called project-based learning. This incorporates projects into everyday learning within classrooms. A study by Condliffe *et al*. (2017) found that students who attended schools that used project-based learning techniques were more likely to attend higher education institutions, but acknowledged that this could be influenced by many other factors[492]. Similarly, Erdogan *et al*. (2016) found from a three-year study that students who experienced a fully implemented STEM project-based learning instructional practice performed better than students who had experienced partially implemented or no such practice and were better placed for college or university admittance[493]. Further, project-based learning had positive effects on Korean students' aspiration to progress to studying STEM at university[494].

Projects can also be one-off, contained experiences, with overlap in the examples of enrichment and extracurricular activities considered in the previous section. Such projects can be done in partnership with a local scientist or a science organisation.

In a review of studies on practical independent research projects, Bennett *et al*. (2018) found that all studies observed an increase in the number of students, indicating that they were more likely to consider a career in science participating in the project. The main reasons for this were increased awareness of the range of science careers and the nature of the work that scientists do[495].

Two studies by Knezek *et al*. (2013, 2019) considered the impact of participating in a hands-on physics project on middle-school students in America. Students measured the power used by various devices while in stand-by, and collated and analysed the data. The authors found that perceptions towards science and science careers became more positive after participating in the project, and that this change was particularly noticeable among girls[496, 497].

Other comparable studies have also found that participating in hands-on projects increased students' interest in science, valuing of science, and/or interest in pursuing further STEM study and careers[498, 499, 500, 501, 502, 503]. Further, work experience placements can provide valuable experiences in undertaking practical inquiry project work, but it is often the case, certainly in England, that few young people have access to such opportunities, particularly those from disadvantaged backgrounds[504, 505, 506].

6.6 Longevity of positive impact of practical inquiry

While there is evidence that practical inquiry in classrooms, extracurricular activities and hands-on projects can all encourage more students to consider progressing to further science study and scientific careers, it is less clear how long the positive effect from an individual experience lasts. A recent longitudinal study by Shahali *et al*. (2020) found that participating in a science project increased students' interest in science and in science careers immediately after the project. Two years on from the project, interest in science had returned back to the level it was pre-project, but interest in science careers remained high[507]. This finding offers further evidence that multiple exposure to practical inquiry is likely to be needed to ignite a long-term passion for science (see Chapter 3).

It is unclear how much impact practical inquiry experiences have on actual progression to further science study and careers. Most of the studies discussed here consider student self-reported interest in science careers, frequently in the form of post-intervention questionnaires. One survey-based study examined how participating in a science project affected students' awareness of science careers and their intended career plans. While girls generally had the largest increase in awareness of science careers, their personal career plans remained mostly unchanged[508].

Relatively few studies examine whether students actually progress into these careers. Of those studies that have considered progression, most survey students who are known to have progressed to STEM, analysing the factors that they felt influenced their choice of study. Some data suggest that extracurricular experiences, such as childhood encounters with the natural world or the influence of a relative or friend, had a greater influence on their career choices than their formal science education[509], indicating the importance of high 'science capital'. Longitudinal data collected between 2009 and 2018, from over 40,000 students aged 10 – 19 in England, indicated that students' aspirations to follow careers in science are shaped by myriad factors (Figure 12), but that it is not easy to discern the extent to which experiences of practical inquiry alone may affect their career aspirations.

6.7 Relative size of positive impact of practical inquiry

Additionally, while most studies referenced here considered the impact of practical inquiry on progression and careers, there is some evidence that learning experiences (such as practical inquiry) will likely have a small impact relative to other factors affecting students' choices in science progression and careers[511, 512]. Understanding the relative impact of these different factors would require large-scale research. This would help to identify which factors are most important for students' progression and career choice, and highlight which, if any, internal factors practical inquiry should aim to increase, in order to maximise impact on progression and careers.

6.8 Conclusions

There is some evidence that participating in practical inquiry directly encourages more students to progress to further science study and scientific careers. This is particularly true for extracurricular experiences and projects. In addition, such experiences may increase students' self-efficacy and outcome expectations of studying science which, along with other factors such as motivation and skills discussed in previous sections of this report, can encourage more students to pursue science further. It is important that all students have access to high-quality practical inquiry, both inside and outside the classroom, since practical inquiry can have a positive impact on most internal factors which influence the choices students make about their study and career plans.

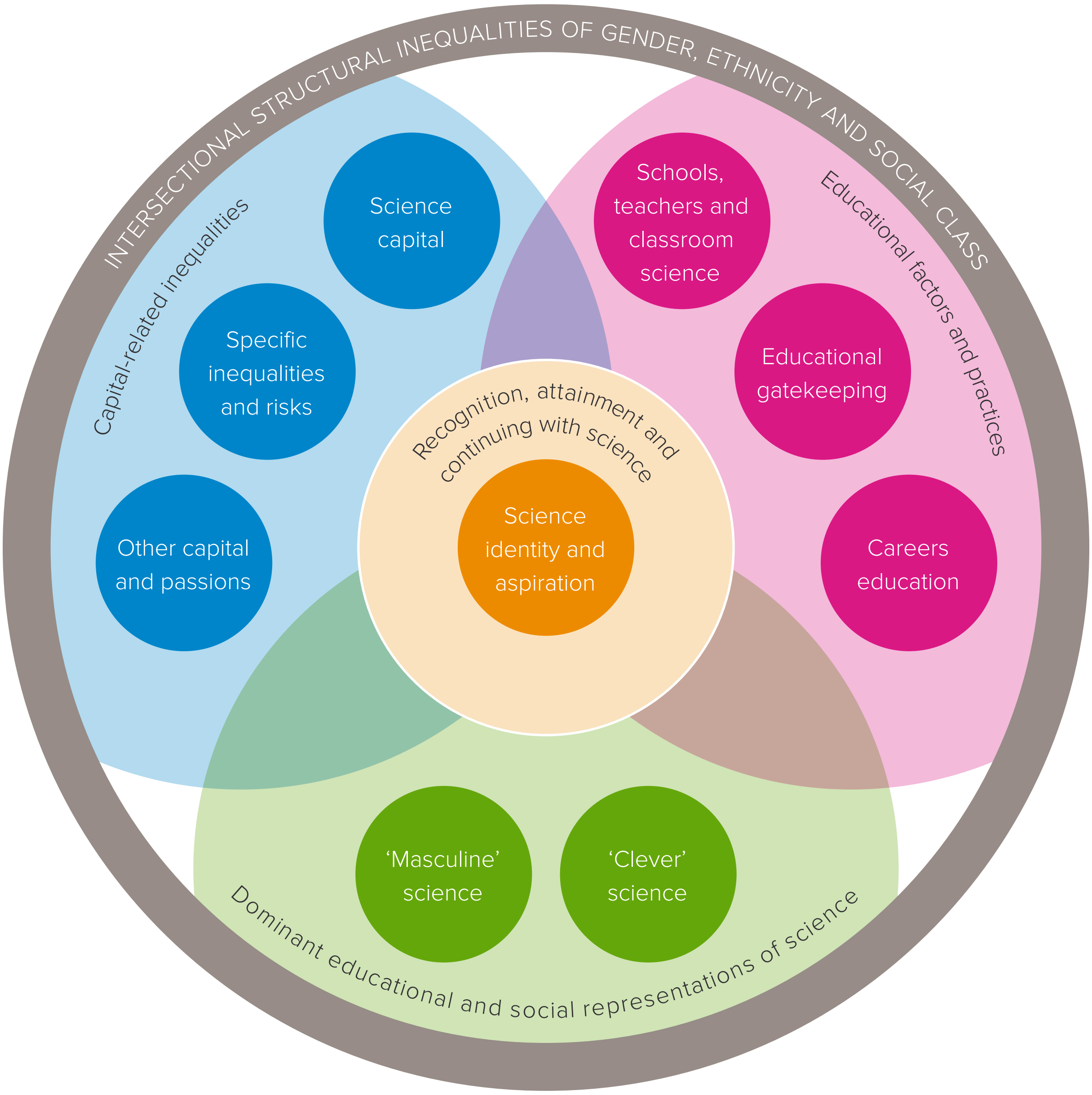
6.9 Limitations

There were relatively few studies that explicitly looked at the impact of practical inquiry on science progression and career aspirations. No meta-analyses addressing this question were uncovered in compiling this evidence synthesis, with most studies instead utilising small-scale survey and case-study data. Such studies were frequently focused on one-off experiences such as projects, rather than everyday practical inquiry in classrooms.

Additionally, as discussed in sections 5 and 6 of this chapter, a lack of longitudinal studies make it difficult to assess the long-term impact of the practical inquiry experiences studied in the literature reviewed. Furthermore, the measure that was often assessed was a survey question relating to career aspirations and interest, rather than data on the actual choices that students made with regards to their study and careers.

FIGURE 12

A model of factors associated with shaping the science identities and aspirations of young people aged 10 – 19[510]



Concluding remarks

Practical inquiry is a fundamental part of science, but its importance cannot be taken for granted. The available evidence suggests that students generally enjoy practical inquiry and find it stimulating. Engaging in practical inquiry may have a positive effect on students' knowledge and understanding of science. It can also support the development of a broad range of physical, cognitive and science process skills and possibly encourage more students to progress to further science study and careers. It needs to be well taught if these positive effects are to be realised.

However, evidence on the efficacy of practical inquiry has been difficult to synthesise because its quality varies greatly. There is a need for more rigorous research, supported by better organised and funded educational research systems, including provision for high-quality longitudinal studies.

Annex 1: Caveats, constraints and complexities

A1.1 Opening remarks

This evidence synthesis has sought to provide a concise, policy-relevant, overview of key issues and evidence, rather than a systematic review. Not all available literature has been covered, partly because the search strategies (see Appendix A1.2.5) did not identify some relevant papers that were later retrieved, eg through reviewing 'grey' literature, and it is possible that some important evidence may have been missed. Inevitably, there are many details and nuances that could not be considered given the scope and length of this study.

Nonetheless, this review included a diverse set of carefully selected articles, informed by expert guidance, and it therefore paints a wide-ranging picture of the current state of understanding of the impacts of practical inquiry on secondary students. Although we consulted with key experts in the field, opinion varies and the information provided may not be representative of all researchers in the relevant fields, or the full range of work conducted (particularly in an international context). Similarly, the relevance – and generalisability – of research findings to different countries, such as the United Kingdom, will vary because educational systems and cultures differ widely across the world.

In addition to the specific limitations set out at the end of each chapter, a range of caveats, constraints and complexities were identified during this study that should be taken into account. These are summarised in the following subsections.

A1.1.1 Accessing relevant research

Whereas the abstracts of scientific and medical research papers normally include precise details of sampling and a clear indication of the results, we found that the investigative literature on practical inquiry is highly variable in this respect. Sometimes it simply was not possible to tell from reading the title, abstract and key words fundamental details such as the sample size or the ages of the participants involved in a study. Therefore, some relevant studies may have been overlooked during initial screening. On other occasions, however, we later had to reject certain studies when it became clear that the sampling or the form of inquiry did not meet our criteria for inclusion, for instance because of a failure to include a control treatment.

A1.1.2 Gaps in the evidence base

The pattern of coverage of research literature on practical inquiry is uneven with respect to the themes of this analysis. While, for instance, many studies focus on the impact of interventions on students' cognition or their enjoyment, attainment in, or attitudes to science, comparatively few explicitly investigate their effects on students' understanding of the norms and behaviours associated with being a scientist, development of wider skills, or their career aspirations. This observation reflects a disconnect between the interests of researchers and the needs of policymakers[513].

In addition, a range of conditions, including funding and the time available, constrains what researchers can practicably investigate and the comprehensiveness with which they can address research questions. These limitations may well explain why most studies focus on immediate, measurable, impacts rather than seeking evidence of longer-term effects, and this has implications for the Quality of research (see section A1.1.4). For instance, while many studies provided detailed information on the socio-economic status or gender of the participants, the discussion of the results often did not focus on these aspects. Furthermore, it is evident that little research has been conducted into the cognitive and non-cognitive impacts of practical inquiry on students with learning disabilities. These examples illustrate that the available evidence in some areas is thin, which limits the extent of analysis and security in the findings.

A1.1.3 Terminology

As discussed in Chapter 1, there is no definitive, universally agreed terminology to describe ‘practical inquiry’. The Gatsby Charitable Foundation concluded from its review that “There is no definitive way to define the different types of practical science, though there have been notable attempts”[514]. Similarly, Schuster *et al*. (2018) point out, “A practical problem is that teachers and researchers alike have a wide range of notions about what actually constitutes inquiry, for what purposes, and what methods are appropriate”[515]: this lack of clarity explains the choice of ‘practical inquiry’ for this report (see Chapter 1), but inevitably the inconsistency of language in cited works prevents this construct from being applied universally. Researchers invariably discuss a range of activities that, at least in part, could be considered to constitute practical inquiry. These are frequently contrasted with strawman caricatures of alternative modes of instruction, in particular, ‘direct instruction’ cast as exposition, memorization, and ‘cookbook’ (or ‘recipe’-style) laboratory work[516] or more mysteriously ‘traditional’ learning. When studies adopt a two-dimensional framework that compares the responses of an experimental group (often doing practical or other inquiry work) with that of a ‘control’ group (often referred to as experiencing ‘traditional science teaching’), it might signify that the researchers have recognised neither the distinctions nor orthogonality of different teaching/ learning axes at play[517].

A1.1.4 Quality of research

The preceding subsections have highlighted weaknesses in the evidence base, notably a:

- lack of standardised abstracts and indexing;
- plethora of confusing terminology;
- focus on addressing what is easily measurable rather than what would be most valuable;
- lack of research into the impact of practical inquiry on students with special educational needs and disabilities.

In addition to these may be added the following:

Lack of replication or scalability

Excluding systematic reviews and meta-analyses, the studies screened for this evidence synthesis suffer from a degree of parochialism. While each piece of research offers its own contribution to the evidence base, and in general is given to demonstrating the validity of the findings and how these uphold (or, perhaps, modify) the established consensus concerning the value or philosophical expectations associated with practical inquiry, there are scarcely any attempts to replicate what others have done or to scale up promising interventions (although some researchers advocate doing this). Consequently, there is still some way to go to understand ‘what works’ in practical inquiry for different types and ages of students as well as in different countries, cultures and school systems.

Short-termism

Much of the research reviewed for this evidence synthesis was concerned with measuring an instantaneous response to an intervention, but this may be of little value because (i) interventions are designed to achieve a measurable positive change of one form or another; and (ii) ultimately what matters is that an intervention, or a series of interventions, has lasting impact. This weakness in the research base is likely to be closely linked to a flawed approach to the funding of much educational research[518].

Confusion among researchers

The quality of any peer-reviewed piece of research inevitably reflects on the researchers conducting it. Nonetheless, this disparaging observation by Schuster *et al*. (2018) is shocking: "researchers too often make such straw man comparisons and misinterpret and misattribute the results they get". Reflecting some concerns already stated, they later add that "Too many studies on inquiry lack operational definitions of type of instruction, use vague or ambiguous terminology, conflate various constructs ... and are not comparative or adequately controlled"[519].

More generally, the measurement of the impact of students' laboratory experience and their inquiry skills "still remains a challenge for educational research"[520], although there has been at least one recent attempt to assess students' inquiry behaviours through machine learning detectors[521]. Notably, Ma & Nickerson's (2006) earlier review observed: "Given that the literature is spread across so many disciplines, it is not surprising that we did not see any agreement on conventions for evaluating the educational effectiveness of labwork. Even the definitions of hands-on labs, simulated labs, and remote labs are inconsistent and confusing"[522].

A1.1.5 Heterogeneity of international jurisdictions

Education systems across the world have varying histories, curricula (which may change), cultural and philosophical traditions, and access to resources (both human and material), which it has generally not been possible to account for in this review.

Wealth, too, may be a decisive factor in determining a country's approach to science education, for instance because laboratories and equipment are costly[523]. As a result of these factors, preferred methods of teaching science differ between countries, with some being more given to practical inquiry approaches than others. Inevitably, these variations affect the nature, focus, approaches to and quantity of educational research and, as previously indicated, findings may not be generalisable.

A1.1.6 'Science' and the sciences

Many of the papers reviewed for this project focus either on 'science' or a specific topic within a scientific discipline. A much more rigorous – and cooperative – approach to international research would be needed to establish consensus about the differential impacts of practical inquiry in the sciences on students as they progress through their secondary education.

A1.2 Methodology

A1.2.1 Scope

This evidence synthesis set out to review the existing evidence on the impacts of practical inquiry in science. The scope of this, as set out in the Introduction, was refined through discussion with Royal Society Fellows, members of the Royal Society's Education Committee and other STEM education experts. Following these discussions, a decision was taken to narrow the scope from all of STEM to the sciences (biology, chemistry, physics, Earth science and environmental science).

A1.2.2 Literature review

To gather academic literature, the team commissioned an information specialist to undertake searches of relevant databases using a search strategy devised in conjunction with the Royal Society.

Initially, searches were initially run to cover publication dates from 2010 – 2020, but upon expert advice, these were subsequently extended to cover the period 2005 – 2009. In addition, some seminal publications published before 2005 were also included. No restriction was placed on language of papers, although all databases were derived mainly from English-language journals and other publications.

Search terms were run on four different databases: Web of Science (Science Citation Index & Social Sciences Citation Index), PsycInfo (Ovid), Education Resources Information Center (Ebsco) and Teacher Reference Center (Ebsco). These searches were conducted between August and November 2020. The searches returned a total of 13,183 results, after partial de-duplication.

Following the search, all articles were screened for inclusion based on reading their titles and abstracts. Initially, the screening process was trialled on a small sample of articles by the whole team and following this, each study was then screened by one member of the team. In cases where team members were uncertain of the inclusion of an article, these articles were highlighted for discussion and reviewed by another team member.

The first round of screening resulted in a shortlist of 1,378 papers. Where appropriate, further studies cited by the articles in this body of literature were included. All papers in this shortlist were then re-reviewed and the details of 530 papers were entered into an extraction template, which captured the following information:

- bibliographical data (eg author(s), title, date of publication);
- the research question(s) to which each paper relates;
- discipline (eg whether a study focuses generically on 'science' or on one or more of the sciences);
- sampling (with respect to age range);
- any especial focus on student characteristics (eg gender, disability, socio-economic status);
- whether a paper's focus is on hands-on or technology-based interventions, or if it covers both; and
- article quality and relevance.

The extraction template was piloted, adapted, and then extraction was then conducted in parallel, with each article being reviewed by one team member.

Not all articles entered into the extraction template are referenced in the evidence synthesis. Some were excluded, for instance because it became evident from reading them in full that they did not actually relate closely to the foci of this report. After discussions with key informants, studies including very small sample sizes (35 or under, ie one class) were also excluded, as were larger studies that failed to attempt to match experimental and control groups.

Where appropriate, very relevant references from the articles reviewed in full-text form were added to the list of articles for review. Additional relevant literature was suggested during key informant interviews, and separate searches were undertaken to identify relevant 'grey' literature (eg policy reports) some of which dated pre-2005. In total, these numbered 116 additional documents.

A1.2.3 Key informant interviews

We interviewed ten key STEM education experts, selected based on desk research and recommendations, to refine the focus of this study and develop a deeper understanding of the issues and evidence relating the impact of practical inquiry on students. Interviews were conducted online using a semi-structured approach and lasted for approximately 50 minutes. The protocol used is detailed below.

Semi-structured interview protocol

Questions

Section 1. Types of practical learning and search criteria

1. What types of teaching and learning approaches do YOU consider fall under the broad category of 'practical learning'?
2. In your experience, which types of 'practical learning' are effective, and what do you consider as the strength of each type?
3. We know that different terms are used to describe practical/inquiry-based learning.
    i. Do you know the reasons for this, and which terms have particular currency within your subject?
    ii. What terminology do you prefer, and why do you favour it?.

Section 2. Refining the scope of the project

4. We wish to gather evidence of impact of practical/inquiry-based learning on secondary pupils in the following domains:
    a. enjoyment of and interest in [the subject];
    b. motivation to study [the subject] in lessons and to consider future study/career in it;
    c. understanding of the culture associated with [the subject];
    d. attainment and progression;
    e. development of specialist and essential employment skills.
    i. Do you know if anything similar has recently been conducted, or is underway now?

ii. Are there other aspects of impact that we should also be looking at and is there any relevant research evidence concerning them?

iii. Should we restrict the international coverage of the project? If so, which countries should we prioritise in investigating good practice, and why?

iv. Have there been particular developments in practice or in educational reform over time we should be aware of that have affected practical/inquiry-based learning? What time-period do you think the project should cover?

v. Could you recommend some key academic papers, policy reports or international studies that specifically focus on the impact of practical learning?

vi. Could you recommend websites or other collections of 'grey' literature?

Section 3. Expectations of the project

5. Since our aim is to produce an evidence synthesis of what is known about the effect of practical learning on educational outcomes, is there anything else we should consider in our design?

6. What would you hope this project might achieve?

A1.2.4 Analysis

Team members reviewed papers for each section of the report and discussed the findings. These findings were then written up, with further reference to the original sources where necessary. The overall messages, focus and evidence gaps that constitute the discussion section were discussed among the team, and written up by a team member. Each section of the synthesis was reviewed by other team members to ensure accuracy and completeness.

A1.2.5 Search strategies

1. ERIC (Ebsco) Strategy searched 1st October 2020. Earlier years 2005–2009 searched 7th November 2020 – 1543 results

S24 S3 AND S13 AND S16 AND S19 AND S22 Limiters - Date Published: 20100101-20201231

6,991

S23 S3 AND S13 AND S19 AND S22 Limiters - Date Published: 20100101-20201231

8,146

S22 S20 OR S21

609,006

S21 TI (((impact N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* N2 review*) or synthesis or evidence or (“program* evaluation” or “project evaluation” or “evaluation research” or “natural experiment*” or “program* effectiveness” or “critical appraisal”)) OR KW (((impact N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* N2 review*) or synthesis or evidence or (“program* evaluation” or “project evaluation” or “evaluation research” or “natural experiment*” or “program* effectiveness” or “critical appraisal”))

25,081

S20 TI (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation)) OR AB (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation)) OR KW (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation)) OR SU (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation OR “literature review*” OR “Outcome measures”))

597,534

S19 S17 OR S18

504,712

S18 (DE “Secondary Education” OR DE “College Preparation” OR DE “Elementary Secondary Education” OR DE “High Schools” OR DE “Junior High Schools” OR DE “Secondary School Students” OR DE “Secondary Schools” OR DE “Grade 6” OR DE “Grade 7” OR DE “Grade 8” OR DE “Grade 9” OR DE “Grade 10” OR DE “Grade 11” OR DE “Grade 12” OR DE “Middle School Students” OR DE “Junior High School Students” OR DE “High School Students”)

463,979

S17 TI ((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12))))) OR AB ((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12))))) OR KW ((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12)))))

190,966

S16 S14 OR S15

998,922

S15 (DE “Academic Achievement” OR DE “Behavior Patterns” OR DE “Study Habits” OR DE “Behavior Change” OR DE “Student Behavior” OR DE “Attitude Change” OR DE “Attitudes” OR DE “Attitude Measures” OR DE “Adolescent Attitudes” OR DE “Childhood Attitudes” OR DE “Educational Attitudes” OR DE “Negative Attitudes” OR DE “Positive Attitudes” OR DE “Preferences” OR DE “Program Attitudes” OR DE “Satisfaction” OR DE “Scientific Attitudes” OR DE “Student Attitudes” OR DE “Motivation” OR DE “Learning Motivation” OR DE “Self Motivation” OR DE “Student Motivation” OR DE “Teacher Motivation” OR DE “Progress Monitoring” OR DE “Cognitive Ability” OR DE “Thinking

Skills” OR DE “Knowledge Level” OR DE “Questioning Techniques” OR DE “Skills” OR DE “Interpretive Skills” OR DE “Research Skills” OR DE “Science Process Skills” OR DE “Study Skills” OR DE “Thinking Skills” OR DE “Creative Thinking” OR DE “Productive Thinking” OR DE “Creativity” OR DE “Personality Traits” OR DE “Norms” OR DE “Career Awareness” OR DE “Career Choice” OR DE “Career Exploration” OR DE “Career Planning” OR DE “Employment Potential” OR DE “Employment Projections”)

373,986

S14 TI ((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*)) OR AB ((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*)) OR KW ((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*))

900,974

S13 S6 OR S9 OR S12

458,119

S12 S10 OR S11

33,686

S11 TI ((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*)) OR AB ((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*)) OR KW ((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*))

12,491

S10 (DE “Laboratory Procedures” OR DE “Laboratory Experiments” OR DE “Field Experience Programs” OR DE “Field Trips” OR DE “Field Instruction” OR DE “Field Studies” OR DE “Science Experiments”)

25,202

S9 S7 OR S8

114,754

S8 SB Program for International Student Assessment OR SB “Trends in International Mathematics and Science Study” OR DE “International Assessment” OR DE “Science Tests” OR DE “Student Evaluation” OR DE “Testing Programs” OR SU “Science Achievement”

49,786

S7 TI ((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*))))) OR AB ((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*))))) OR KW ((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*)))))

83,837

S6 S4 OR S5

364,924

S5 TI (((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”)))) OR AB (((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”)))) OR KW (((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”))))

81,547

S4 (DE “Problem Based Learning” OR DE “Active Learning” OR DE “Discovery Learning” OR DE “Experiential Learning” OR DE “Inquiry” OR DE “Problem Solving” OR DE “Electronic Learning” OR DE “Cooperative Learning” OR DE “Student Centered Learning” OR DE “Group Discussion” OR DE “Science Course Improvement Projects” OR DE “Teaching Methods” OR DE “Elementary School Science” OR DE “Scientific Literacy” OR DE “Hands on Science” OR DE “Science Education” OR DE “Science Experiments” OR DE “Science Instruction” OR DE “Science Curriculum” OR DE “Secondary School Science” OR DE “Science Programs” OR DE “Summer Science Programs” OR DE “Science Interests” OR DE “STEM Education”)

338,064

S3 S1 OR S2

170,409

S2 TI (science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”) OR AB (science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”) OR KW (science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”)

150,679

S1 (DE “Biology” OR DE “Biological Sciences” OR DE “Chemistry” OR DE “Physics” OR DE “Earth Science” OR DE “Sciences”)

58,378

2. Web of Science (Science Citation Index & Social Sciences Citation Index) – Searched 7th October 2020. Earlier years 2005-2009 Searched 7th November 2020 – 211 results

11 1,423

#10 AND #7 AND #6 AND #5 AND #1

Indexes=SCI-EXPANDED, SSCI

Timespan=2010-2020

10 8,503,825

#9 OR #8

9 882,177

TI=((impact NEAR/2 (evaluat* OR assess* OR analy* OR estimat* OR measur*)) OR (effect* NEAR/2 (evaluat* OR assess* OR analy* OR estimat* OR measur*)) OR (systematic* NEAR/2 review*) OR synthesis OR evidence OR (“program* evaluation” OR “project evaluation” OR “evaluation research” OR “natural experiment*” OR “program* effectiveness” OR “critical appraisal”))

8 7,874,275

TS=(random* OR experiment* OR outcome OR (match* NEAR/2 (propensity OR coarsened OR covariate)) OR “propensity score” OR “difference in difference*” OR “difference-in-difference*” OR “differences in difference*” OR “differences-in-difference*” OR “double difference*” OR “quasi-experimental” OR “quasi experimental” OR “quasi-experiment” OR “quasi experiment”

OR ((estimator OR counterfactual) AND evaluation*) OR "instrumental variable*" OR (iv NEAR/2 (estimation OR approach)) OR "regression discontinuity" OR "time series" OR "segment* regression" OR (non NEAR/2 participant*) OR ((control OR comparison) NEAR/2 (group* OR condition* OR area* OR intervention)) OR "verbal report*" OR coding OR diary OR diaries OR ((discourse OR conversation*) NEAR/2 analysis) OR ethnograph* OR "grounded theory" OR "mixed research method*" OR "mixed method*" OR "narrative inquiry" OR "narrative enquiry" OR non-observational OR nonobservational OR ((nonparticipant OR non-participant*) NEAR/3 observ*) OR survey OR view OR views OR telephon* OR "case study" OR observation)

7 112,670

TS=(((secondary OR middle OR senior) NEAR/3 (education OR school*)) OR "high school*" OR (grade NEAR/1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12)))

6 9,031,445

TS=(impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*)

5 604,408

#4 OR #3 OR #2

4 179,429

TS=((lab OR laboratory OR field* OR "hands on" OR hands-on) NEAR/2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*))

3 79,047

TS=("Program for International Student Assessment" OR "Trends in International Mathematics and Science Study" OR pisa OR timss OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) NEAR/3 (student* OR pupil*)))

2 358,499

TS=(((problem* OR project* OR inquiry* OR enquiry*) NEAR/2 based) OR "extended project*" OR epq OR ((active OR discovery OR experiential) NEAR/2 learning) OR (problem* NEAR/2 solv*) OR ((cooperative OR co-operative OR collaborat* OR student-centered OR student-centred OR group-based) NEAR/2 learning) OR "group discussion*")

1 1,237,182

TS=(science* OR biology OR "biological science*" OR chemistry OR physics OR "physical science*" OR "environmental science*" OR "earth science*")

3. PsycInfo (Ovid) <1806 to September Week 4 2020> Searched 7th October 2020. Earlier years 2005-2009 searched 7th November 2020 – 479 results

1 (science* or biology or "biological science*" or chemistry or physics or "physical science*" or "environmental science*" or "earth science*").ti,ab. (168703)

2 sciences/ or biology/ or botany/ or zoology/ or chemistry/ or physics/ or ecology/ or environmental education/ or exp science education/ or STEM/ (46864)

3 or/1-2 (182402)

4 (((problem-* or project-* or inquiry-* or enquiry-*) adj2 based) or "extended project*" or epq or ((active or discovery or experiential) adj2 learning) or (problem* adj2 solv*) or ((cooperative or co-operative or collaborat* or student-centered or student-centred or group-based) adj2 learning) or "group discussion*"). ti,ab. (806672)

5 ("Program for International Student Assessment" or "Trends in International Mathematics and Science Study" or pisa or timss or ((assess* or test* or evaluat* or apprais* or measur*) adj3 (student* or pupil*))). ti,ab. (43281)

6 ((lab or laboratory or field* or "hands on"

or hands-on) adj2 (experiment* or practical* or investigat* or demonstrat* or work or course*)).ti,ab. (17665)

7 collaborative learning/ or collaboration/ or cooperative learning/ or group discussion/ or group instruction/ or problem based learning/ or school learning/ (33872)

8 teaching methods/ or group instruction/ or individualized instruction/ or open classroom method/ or programmed instruction/ or educational laboratories/ or educational measurement/ or curriculum based assessment/ or formative assessment/ or "grading (educational)"/ (62229)

9 or/4-8 (907739)

10 (impact or behavio* or attitud* or motivat* or enjoy* or progress* or self-efficacy or cognit* or knowledge or understanding or attain* or skill* or curiosity or curious or question* or achiev*).ti,ab. (2610532)

11 academic achievement/ or academic overachievement/ or academic underachievement/ or achievement gap/ or science achievement/ or academic achievement motivation/ or academic achievement prediction/ or academic self concept/ or educational attainment level/ or self-efficacy/ or academic self concept/ or exploratory behavior/ or curiosity/ (97135)

12 or/10-11 (2624077)

13 (((secondary or middle or senior) adj3 (education or school*)) or "high school*" or grade).ti,ab. (184357)

14 high school students/ or high schools/ or high school education/ or secondary education/ or junior high school students/ or junior high schools/ or middle schools/ or middle school students/ (64321)

15 or/13-14 (198623)

16 (random* or experiment* or outcome or (match* adj2 (propensity or coarsened or covariate)) or "propensity score" or "difference in difference*" or "difference-in-difference*" or "differences in difference*" or "differences-in-difference*" or "double difference*" or "quasi-experimental" or "quasi experimental" or "quasi-experiment" or "quasi experiment" or ((estimator or counterfactual) and evaluation*) or "instrumental variable*" or (iv adj2 (estimation or approach)) or "regression discontinuity" or "time series" or "segment* regression" or (non adj2 participant*) or ((control or comparison) adj2 (group* or condition* or area* or intervention)) or "verbal report*" or coding or diary or diaries or ((discourse or conversation*) adj2 analysis) or ethnograph* or "grounded theory" or "mixed research method*" or "mixed method*" or "narrative inquiry" or "narrative enquiry" or non-observational or nonobservational or ((nonparticipant or non-participant*) adj3 observ*) or survey or view or views or telephon* or "case study" or observation).ti,ab. (1380748)

17 ((impact adj2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* adj2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* adj2 review*) or synthesis or evidence or ("program* evaluation" or "project evaluation" or "evaluation research" or "natural experiment*" or "program* effectiveness" or "critical appraisal")).ti. (98143)

18 experimental methods/ or mixed methods research/ or quantitative methods/ or quasi experimental methods/ or "systematic review"/ or exp experimental design/ or exp randomized controlled trials/ or time series/ or exp qualitative methods/ (86393)

19 exp Course Evaluation/ or exp Educational Program Evaluation/ or exp Teacher Effectiveness Evaluation/ (10652)

20 or/16-19 (1490294)

21 3 and 9 and 12 and 15 and 20 (3287)

22 limit 21 to yr="2010 -Current" (2122)

4. Teacher Reference Center (Ebsco) – Searched 11th October 2020. Earlier years 2005-2009 searched 7th November 2020 – 150 results

S11 S1 AND S5 AND S6 AND S7 AND S10

Limiters - Published Date: 20101001-20201231

401

S10 S8 OR S9

138,089

S9 TI (((impact N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* N2 review*) or synthesis or evidence or (“program* evaluation” or “project evaluation” or “evaluation research” or “natural experiment*” or “program* effectiveness” or “critical appraisal”)) OR (((impact N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* N2 review*) or synthesis or evidence or (“program* evaluation” or “project evaluation” or “evaluation research” or “natural experiment*” or “program* effectiveness” or “critical appraisal”)) OR SU(((impact N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* N2 review*) or synthesis or evidence or (“program* evaluation” or “project evaluation” or “evaluation research” or “natural experiment*” or “program* effectiveness” or “critical appraisal”)) OR (((impact N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (effect* N2 (evaluat* or assess* or analy* or estimat* or measur*)) or (systematic* N2 review*) or synthesis or evidence or (“program* evaluation” or “project evaluation” or “evaluation research” or “natural experiment*” or “program* effectiveness” or “critical appraisal”))

30,831

S8 TI (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation)) OR AB (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation)) OR KW (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation)) OR SU (((random* or experiment* or outcome OR (match* N2 (propensity or coarsened or covariate)) or “propensity score” or (“difference in difference*” or “difference-in-difference*” or “differences in difference*” or “differences-in-difference*” or “double difference*”) or (“quasi-experimental” or “quasi experimental” or “quasi-experiment” or “quasi experiment”) or ((estimator or counterfactual) and evaluation*) or “instrumental variable*” or (IV N2 (estimation or approach)) or “regression discontinuity” or “time series” or “segment* regression” or (non N2 participant*) or ((control or comparison) N2 (group* or condition* or area* or intervention)) or “verbal report*” or coding or diary or diaries or ((discourse or conversation*) N2 analysis) or ethnograph* or “grounded theory” or “mixed research method*” or “mixed method*” or “narrative inquiry” or “narrative enquiry” or non-observational or nonobservational or ((nonparticipant or non-participant*) N3 observ*)) or survey or view or views or telephon* or “case study” or observation OR “literature review*” OR “Outcome measures”))

118,834

S7 TI ((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12))))) OR AB ((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12))))) OR KW ((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12))))) OR SU((((((secondary OR middle OR senior) N3 (education OR school*)) OR “high school*” OR (grade N1 (6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12)))))

65,313

S6 TI ((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*)) OR AB ((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*)) OR ((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*)) OR SU((impact OR behavio* OR attitud* OR motivat* OR enjoy* OR progress* OR self-efficacy OR cognit* OR knowledge OR understanding OR attain* OR skill* OR curiosity OR curious OR question* OR achiev*))

258,799

S5 S2 OR S3 OR S4
42,470

S4 TI ((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*)) OR AB ((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*)) OR KW ((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*)) OR SU((lab OR laboratory OR field* OR “hands on” OR hands-on) N2 (experiment* OR practical* OR investigat* OR demonstrat* OR work OR course*))
3,704

S3 TI ((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*))))) OR AB ((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*))))) OR KW ((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*))))) OR SU((“Program for International Student Assessment” OR “Trends in International Mathematics and Science Study” OR PISA OR TIMSS OR ((assess* OR test* OR evaluat* OR apprais* OR measur*) N3 (student* OR pupil*)))))
18,762

S2 TI (((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”)))) OR AB (((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”)))) OR KW (((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”)))) OR SU(((((problem-* OR project-* OR inquiry-* OR enquiry-*) N2 based) OR “extended project*” OR EPQ OR ((active OR discovery OR experiential) N2 learning) OR (problem* N2 solv*))) OR ((((cooperative OR co-operative OR collaborat* or student-centered OR student-centred OR group-based) N2 (learning)) OR “group discussion*”))))
22,474

S1 TI (science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”) OR AB (science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”) OR KW (science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”) OR SU(science* OR biology OR “biological science*” OR chemistry OR physics OR “physical science*” OR “environmental science*” OR “earth science*”)
108,557

Annex 2: Acknowledgements

Interviewees	
Professor Judith Bennett	Salters' Professor of Science Education, University of York
Dr Alison Clark-Wilson	Principal Research Associate and Connected Learning Lead (IOE-CCM), UCL Knowledge Lab, UCL Institute of Education
Professor Paul Curzon	Professor of Computer Science, Queen Mary University of London
Professor Sally Fincher	Professor of Computing Education, University of Kent
Dr Janet Hanson	Researcher, Centre for Real-World Learning, The University of Winchester
Professor Christine Harrison	Professor in Science Education, King's College London
Professor Jeremy Hodgen	Professor of Mathematics Education, UCL Institute of Education
Sir James Hough OBE FRS	Associate Director, Institute for Gravitational Research, University of Glasgow
Professor Bill Lucas	Director, Centre for Real-World Learning, The University of Winchester
Mr Matt McLain	Liverpool John Moores University
Dr Rosalyn Roberts	University of Durham
Dr Janet Hanson	Centre for Real-World Learning, The University of Winchester

Royal Society Staff	
Ms Elizabeth Chambers	Schools Engagement Officer (secondment April – July 2020)
Mr Edward Clarke	Project Coordinator (April 2020 – May 2021), Policy Adviser (from May 2021)
Ms Anna Dewar*	UKRI Intern, September – December 2020
Mr David Montagu	Policy Adviser (Senior Policy Adviser from April 2023) and Project Lead
*Anna was awarded her doctorate shortly after completing her internship.	

This report has been reviewed by an independent panel of experts. The reviewers were asked to act as independent referees of the report's technical content and presentation. They acted in a personal and not a representative capacity. The Royal Society gratefully acknowledges the contribution of the reviewers.

Reviewers	
Professor Judith Bennett	Salters' Professor of Science Education, University of York
Sir John Holman	Senior Adviser in Education, Gatsby Charitable Foundation
Professor Tom McLeish FRS[xi]	Professor of Natural Philosophy, Department of Physics, University of York
Professor Michael Reiss	Professor of Science Education, UCL Institute of Education
Sir Steve Sparks CBE FRS	Emeritus Professor, University of Bristol

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[xi] Very sadly, Tom McLeish passed away on 27 February 2023.

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