Research and analysis

Research review series: science

Published 29 April 2021

Applies to England

Contents

This publication is available at https://www.gov.uk/government/publications/research-review-series-science/research-review-series-science

Introduction

This review explores the literature relating to the field of science education. Its purpose is to identify factors that can contribute to high-quality school science curriculums, assessment, pedagogy and systems. We will use this understanding of subject quality to examine how science is taught in England's schools. We will then publish a subject report to share what we have learned.

The purpose of this research review and the intended audience is outlined more fully in the 'Principles behind Ofsted's research reviews and subject reports'.[footnote 1]

Since there are a variety of ways that schools can construct and teach a high-quality science curriculum, it is important to recognise that there is no singular way of achieving high-quality science education.

In this review, we have:

- outlined the national context in relation to science
- summarised our review of research into factors that can affect quality of education in science
- considered curriculum progression in science, pedagogy, assessment and the impact of school leaders' decisions on provision

The review draws on a range of sources, including our 'Education inspection framework: overview of research' and our 3 phases of curriculum research.[footnote 2]

We hope that through this work, we will contribute to raising the quality of science education for all young people.

Ambition for all

Summary

> The performance of pupils who study science in England is significantly above the average performance of pupils in other countries. Over the past 10 years, there has been an increase in the number of pupils wanting to study science beyond age 16. However, there is emerging evidence from the Trends in International Mathematics and Science Study (TIMSS), key stage 2 national sample tests and Ofsted's own research into curriculum that suggests the picture is not an improving one for all pupils and may be deteriorating. This makes the findings of this review particularly significant, not only because it identifies features associated with high-quality science education but because it also shines a light on some of the barriers that prevent their implementation.

Aims of science education

Science has been designated a core subject of the national curriculum, alongside mathematics and English, since the Education Reform Act of 1988. As such, a science education forms an important entitlement for all young people.[footnote 3]

Although the precise purposes of science education have been contested for some time,[footnote 4] there is general consensus that it involves pupils learning a body of knowledge relating to the products and practices of science.[footnote 5] By learning about the products of science, such as atoms and cells, pupils are able to explain the material world and 'develop a sense of excitement and curiosity about natural phenomena'.[footnote 6] By learning about the practices of science, pupils learn how scientific knowledge becomes established through scientific enquiry. By learning this, pupils appreciate the nature and status of scientific knowledge: for example, knowing it is open to revision in the light of new evidence.

As pupils learn science, they also learn about its uses and significance to society and their own lives.[footnote 7] This will highlight the significant contribution science has made in the past. For example, by eradicating smallpox and discovering penicillin. But pupils will also learn about the continuing importance of science in solving global challenges such as climate change, food availability, controlling disease and access to water.[footnote 8]

Science education also provides the foundation for a range of diverse and valuable careers that are crucial for economic, environmental and social development. [footnote 9]

National context

Primary and the early years foundation stage

Pupils begin their formal science education in the early years foundation stage (EYFS). This involves learning foundational knowledge primarily through the 'understanding the world: the natural world'[footnote 10] area of learning. This provides a number of rich contexts for pupils to learn a wide range of vocabulary. [footnote 11] These words form the beginnings of scientific concepts that will be built on in Year 1 and beyond. Because pupils develop their scientific and non-scientific vocabulary during this time, the EYFS should not just be considered as preparation for learning further science in Year 1.

At primary school, the national curriculum outlines what content pupils learn.[footnote 12] However, there is concern that science is being squeezed out of the primary school curriculum. This has coincided with the removal of primary national curriculum tests.[footnote 13] For example, a 'state of the nation' report for primary science education in 2020 revealed that, when taught weekly, science is taught for an average of 1 hour and 24 minutes per week.[footnote 14] On average, younger year groups received fewer hours of weekly lessons. Only 31% of respondents to the same survey said their senior leaders saw science as 'very important'. This contrasts with 88% for English and 86% for mathematics.

Ofsted's own research into the primary curriculum highlights a similarly concerning picture.[footnote 15] Inspectors found that, in the majority of primary schools, disproportionate amounts of curriculum time were being spent on English and mathematics, often to prepare for tests. This significantly reduced the amount of curriculum time available to teach science, which in turn led to narrowing of the curriculum.

Evidence of a decline in primary science is further supported by the performance of Year 6 pupils in biennial national sample tests.[footnote 16] In 2018, just 21.2% of the 8,139 Year 6 pupils tested were estimated to have reached the expected standard in science.[footnote 17] This is a decrease of nearly 7 percentage points since 2014 when the current methodology for national sample tests was first introduced.[footnote 18] While such paper and pencil tests cannot measure all the important outcomes of a science education, they are nevertheless an important indicator of curriculum impact.

A recent report from The Ogden Trust and The University of Manchester describes the realities of primary pupils' science learning.[footnote 19] It shows that pupils regularly experience 'fun activities' without developing a deep understanding of the associated scientific concepts. Indeed, a recent survey shows that only just over half of pupils in Years 7 and 8 felt that the science they had learned in primary school prepared them well for learning science at secondary school.[footnote 20]

This decline in the status of primary science is particularly concerning given the importance of these foundational years in influencing pupils' scientific aspirations[footnote 21] and future learning.[footnote 22]

Secondary

In England, science is assessed at key stage 4 as either combined science worth 2 GCSE grades, or as 3 separate science GCSEs, commonly referred to as triple science. A minority of pupils complete entry level or vocational qualifications. At key stage 5, pupils can choose to study A levels in the 3 sciences, as well as environmental science. There is also a range of vocational science qualifications. Health and science T levels begin in autumn 2021.[footnote 23]

In 2019, 26.6% of pupils were entered for triple science and just over 95% of pupils were entered for English Baccalaureate (EBacc) science.[footnote 24] This is an increase of over 30 percentage points since the EBacc science measure was first introduced in 2010. This has coincided with a large decrease in the number of pupils being entered for BTEC applied science at key stage 4.[footnote 25] The number of pupils studying A levels in biology, chemistry and physics is also encouraging, being at its highest level for 10 years in 2019.[footnote 26]

Despite the increase in the number of pupils wanting to study the sciences beyond age 16, it is important to remember that these pupils are the exception.[footnote 27] Indeed, research shows that many pupils leave school without a basic knowledge or appreciation of science[footnote 28] and that their interest declines with time spent at school.[footnote 29] Often, this decrease in interest and motivation occurs when pupils have to make so-called 'choices' about science pathways.[footnote 30] For example, many pupils wrongly assume that science is not for them when they are prevented from choosing triple science at GCSE. This is particularly problematic when the decision to study triple science comes too early.

Evidence from analysis of school timetables in England suggests that insufficient time is often allocated to teach triple science.[footnote 31] This means that some schools restrict triple science to just high-attaining pupils who are presumed to be able to cope with the more intensive timetable.

Recent findings from TIMSS 2019 show that England's performance in science at Year 9 has decreased significantly compared with 2015, albeit remaining well above the TIMSS average.[footnote 32] England's performance is now significantly lower than in any previous TIMSS cycle. This contrasts with the trend in mathematics achievement, which has seen an increase in the performance of Year 9 pupils over the last 24 years. Of particular concern is the widening gap between the highest- and lowest-performing Year 9 pupils in science. Indeed, the proportion of pupils performing below the lowest TIMSS science benchmark has doubled since 2015.

Research commissioned by the Education Endowment Foundation shows that disadvantaged pupils make poorer progress in science at every stage of their education, although this gap is not unique to science.[footnote 33] These pupils are also less likely to take a science subject at A level and beyond.

Workforce challenges

Any attempt to capture the national context for science education needs to recognise that schools face a number of challenges in recruiting and retaining specialist science teachers.

The 2019 school workforce census shows that 26.6% of teaching hours in physics were taught by teachers with no relevant post-A-level qualifications.[footnote 34] The figure was 17.3% and 6.9% for chemistry and biology respectively. At primary, estimates suggest that just 5% of teachers hold specialised science degrees and teaching qualifications.[footnote 35]

Recruitment into teacher training is also challenging. Although in 2019 the number of trainees specialising in biology exceeded the Department for Education's recruitment target, chemistry and physics targets were missed. They reached only 70% and 43%, respectively.[footnote 36]

Curriculum progression: what it means to get better at science

Summary

> The school science curriculum sets out what it means 'to get better' at science. Expertise in science requires pupils to build at least 2 forms, or categories, of knowledge. The first is 'substantive' knowledge, which is knowledge of the products of science, such as models, laws and theories. The second category is 'disciplinary knowledge', which is knowledge of the practices of science. This teaches pupils how scientific knowledge becomes established and gets revised. Importantly, this involves pupils learning about the many different types of scientific enquiry. It should not be reduced to learning a single scientific method. In high-quality science curriculums, knowledge is carefully sequenced to reveal the interplay between substantive and disciplinary knowledge. This ensures that pupils not only know 'the science'; they also know the evidence for it and can use this knowledge to work scientifically.

Learning science: from novice to expert

Research exploring the differences between expert and novice scientists is useful to inform our understanding of what successful learning in science looks like. Experts differ from novices not only in the extent of their domain-specific knowledge, but also in how this knowledge is organised in their memory.[footnote 37] Experts know more science than novices and this knowledge is better structured. When knowledge is well structured, it becomes meaningful, flexible and easier to access. This knowledge can then be used to solve complex, and interesting, scientific problems without overloading working memory.[footnote 38]

Organisation of these cognitive structures is a good predictor of pupils' problem-solving abilities in science.[footnote 39] Expert pupils organise their knowledge according to major scientific principles, such as conservation of energy. They then use these principles to solve problems.[footnote 40] Expertise in science is also associated with being able to connect knowledge between different levels when thinking about problems.[footnote 41] This might, for example, involve explaining what is happening at the cellular level by referring to what molecules are doing at the submicroscopic level.

There are at least 2 important implications of this research for establishing our understanding of a high-quality science education.

First, because expertise comes from domain-specific knowledge and not generic skills,[footnote 42] pupils need to develop an extensive and connected knowledge base. When pupils learn new knowledge, it should become integrated with the knowledge they already have. This ensures that learning is meaningful.[footnote 43] In science, pupils need their knowledge to be organised around the most important scientific concepts, which predict and explain the largest number of phenomena.[footnote 44] An ambitious curriculum therefore needs to identify the most important concepts for pupils to learn. It must also teach pupils how these concepts are related so that, over time, the logical structure of each scientific discipline is made explicit.[footnote 45] For example, pupils studying biology should learn how the theory of evolution provides a central structure to organise and connect many other concepts such as variation, adaptation and natural selection.

Second, the limited capacity of human working memory means that the curriculum should break down complex concepts and procedures into meaningful ‘chunks’ of content.[footnote 46] These ‘chunks’, or components, can then be sequenced in the curriculum over time. This allows pupils to successfully build knowledge of science concepts and their relationships over multiple years, without working memory being overloaded.

Pupils’ success in learning science and, as a result, their perception of being ‘good’ at it are crucial for developing their interest in the subject. For example, research shows that a lack of confidence is a key contributor towards girls’ reluctance to study physics at A level.[footnote 47]

How this review classifies scientific knowledge

As outlined above, at the core of scientific expertise lies extensive, connected knowledge. This means that as pupils travel through the school curriculum, they need to build their knowledge of scientific concepts and procedures. By doing so, pupils can reason scientifically about phenomena with increasing sophistication and can use their knowledge to work scientifically with increasing expertise.

A useful framework for constructing science curriculums makes the distinction between the following:

- **substantive knowledge** (knowledge of the products of science, such as concepts, laws, theories and models):[footnote 48] this is referred to as scientific knowledge and conceptual understanding in the national curriculum
- **disciplinary knowledge** (knowledge of how scientific knowledge is generated and grows): this is specified in the ‘working scientifically’ sections of the national curriculum and it includes knowing how to carry out practical procedures

This type of distinction is useful for curriculum design because it reflects how knowledge is arranged and used in the sciences.[footnote 49] By learning substantive and disciplinary knowledge, pupils not only know ‘the science’; they also know the evidence for it.

Substantive knowledge: the products of science

Substantive knowledge in science is organised according to the 3 subject disciplines: biology, chemistry and physics. Earth science is frequently considered to be a fourth but is typically taught through the other 3 disciplines in England’s schools. Each discipline has its own ontological, methodological and epistemic rules.[footnote 50] But they all belong to ‘science’ because they are disciplines that explain the material world. Within each discipline, there are subdisciplines[footnote 51] such as cell biology, electromagnetics and organic chemistry. These are characterised by the methods and scientific theories they use.

Each scientific discipline gives pupils a unique perspective to explain the world around them. This means that as pupils progress through the curriculum, they need to develop knowledge about the similarities and the differences between each scientific discipline.[footnote 52] Biology, for example, seeks to understand living organisms and life. It must take account of complex systems involving interactions between genes, the environment and random chance.[footnote 53] Physics, in contrast, typically assumes that entities behave identically. It 'builds its explanations on measurable quantities that can be put into numerical relationships'.[footnote 54] Chemistry differs again in that it draws heavily on the use of models and modelling[footnote 55] to explain the behaviour of matter and routinely involves the synthesis of the objects it studies.[footnote 56]

Despite these differences, each discipline draws extensively on common concepts too, such as energy and the particle model. This means that there should be a clear rationale for when and where these inter-disciplinary concepts are first introduced in the curriculum and how they develop over time.[footnote 57] Pupils will also need to learn that important scientific discoveries, such as the structure of DNA, are often made by scientists from different disciplines working together.

Disciplinary knowledge: knowing how science establishes knowledge through scientific enquiry

Disciplinary knowledge is a curricular term. It describes what pupils learn about the diverse ways[footnote 58] that science establishes and grows knowledge through scientific enquiry.

Acquiring disciplinary knowledge is an important goal of the national curriculum.[footnote 59] This goes beyond simply doing practical work or collecting data.[footnote 60] It includes learning about the concepts and procedures that scientists use to develop scientific explanations which, in turn, have implications for the status and nature of the scientific knowledge produced.[footnote 61]

The national curriculum specifies what disciplinary knowledge pupils will need to know and remember through the 'working scientifically' sections of the programmes of study.[footnote 62]

There are at least 4 content areas[footnote 63] through which pupils make progress when learning disciplinary knowledge:

1. **Knowledge of methods that scientists use to answer questions.** This covers the diverse methods that scientists use to generate knowledge,[footnote 64] not just fair testing, which is often over emphasised in science classrooms and curriculums.[footnote 65] For example, use of models, chemical synthesis, classification, description and the identification of correlations (pattern-seeking) have played important roles, alongside experimentation, in establishing scientific knowledge.[footnote 66]
2. **Knowledge of apparatus and techniques, including measurement.** This covers how to carry out specific procedures and protocols safely and with proficiency in the laboratory and field. This is a particularly important area for

enabling progression on to science courses beyond GCSE and at university.[footnote 67] It includes the accurate measurement and recording of data. Pupils learn that all measurement involves some error and scientists put steps in place to reduce this.

3. **Knowledge of data analysis.** This covers how to process and present scientific data in a variety of ways to explore relationships and communicate results to others. Pupils learn about different types of tables and graphs and how to identify correlations.
4. **Knowledge of how science uses evidence to develop explanations.** This covers how evidence is used, alongside substantive knowledge, to draw tentative but valid conclusions. It includes the distinction between correlation and causation and knowing that explanation is distinct from data and does not simply emerge from it.[footnote 68] Pupils learn how scientific models, laws and theories develop over time, including the importance of technology and the role of the scientific community in peer review.

Research shows that disciplinary knowledge is often framed as only 'skills' in school curriculums and pupils are assumed to pick up these skills by 'doing'.[footnote 69] However, this assumption fails to recognise that disciplinary thinking and carrying out practical investigations skilfully are dependent on pupils having learned a domain of knowledge.[footnote 70]

It is therefore important to recognise that disciplinary knowledge, like substantive knowledge, is underpinned by knowledge of procedures **and** concepts (Table 1). The curriculum therefore needs to break down complex disciplinary practices, such as drawing graphs, validating experimental data or using a thermometer, into their component knowledge.[footnote 71] The curriculum can then outline how pupils' disciplinary knowledge advances over time.[footnote 72]

Table 1: Knowledge can be categorised according to its disciplinary nature and how it is used by an individual

	Substantive knowledge	**Disciplinary knowledge**
Conceptual… know that… because…	Liquids expand when they are heated (for example, the liquid inside a thermometer).	All measuring instruments, such as a thermometer, have a built-in degree of uncertainty.
Procedural[footnote 73]… know how to… and be able to…	Draw a particle diagram for a liquid.	Use a thermometer to measure the temperature of a solution.

Scientific enquiry integrates substantive and disciplinary knowledge, as explained in the table above, into an overall strategy to answer questions about the material world.

Disciplinary and substantive knowledge: the importance of interplay

There is a risk that by categorising knowledge as either disciplinary or substantive in the curriculum, it is taught separately. For example, pupils may be taught disciplinary knowledge only in standalone 'skills' units. This should be avoided.[footnote 74] A curriculum focusing on either substantive or disciplinary knowledge leads to at least 2 problematic models of curriculum design that misrepresent the discipline of science.

The first problematic curriculum model treats science as only a body of substantive knowledge. Here, pupils learn substantive facts but are unaware of how this knowledge developed and became accepted. This leads to pupils developing a naive understanding of the status of scientific knowledge.[footnote 75] For example, they may think Darwin's theory of evolution is simply a good guess or that 'science is complete'. A focus on only substantive knowledge may also lead to misconceptions. Pupils may, for example, think a picture of a scientific model of an atom inside a textbook is what an atom is, rather than seeing it as a representation. By viewing science as complete, pupils are also unable to respond intelligently to scientific information in the real world,[footnote 76] which often involves contradictory claims being made from the same data.

At the other extreme, a curriculum that focuses only on working scientifically (disciplinary knowledge) is equally problematic. This type of curricular thinking is often associated with the 'process view' that characterises science by its methods.[footnote 77] Curriculums adopting this view of science focus on teaching general skills such as 'observing' or 'classifying' that are assumed to be generalisable across different domains of knowledge. This is problematic. It unintentionally disregards the importance of content and context in science. Research identifies that skills such as observation[footnote 78] or identifying significant variables[footnote 79] depend on context and substantive knowledge. This is because what scientists observe, or choose to control in an experiment, depends on what they know. For example, classifying flowering plants scientifically requires knowledge of floral parts to place specimens in appropriate groups. However, classifying insects requires knowledge of body parts.

A solution to these problems is to organise the school curriculum so that disciplinary knowledge is embedded within the substantive content of biology, chemistry and physics. This enables pupils to see the important interplay between both categories of knowledge, allowing pupils to:

- appreciate the nature of substantive knowledge by knowing the evidence for it
- use disciplinary knowledge together with substantive knowledge to ask and answer scientific questions by carrying out different types of scientific enquiry
- recognise the power and limitations of science and consider associated personal, social, economic and environmental implications. This includes making decisions based on scientific evidence and learning about socio-scientific issues

Scientific enquiry and enquiry-based instruction are not the same

We will consider research relating to enquiry-based instruction later, in relation to pedagogy. However, it is important to clarify at this point that disciplinary knowledge of scientific enquiry, that forms a curricular goal and enables pupils to work scientifically, should not be confused with enquiry-based teaching approaches.[footnote 80] These are pedagogical approaches that aim to develop pupils' scientific knowledge by getting them to take part in practices that resemble some aspects of scientific enquiry.

Based on the above, high-quality science education may have the following features

- The curriculum is planned to build increasingly sophisticated knowledge of the products (substantive knowledge) and practices (disciplinary knowledge) of science.
- Disciplinary knowledge (identified in the 'working scientifically' sections of the national curriculum) comprises knowledge of concepts as well as procedures.
- When pupils develop their disciplinary knowledge, they learn about the diverse ways that science generates and grows knowledge through scientific enquiry. This is not reduced to a single scientific method or taken to mean just data collection.
- The curriculum outlines how disciplinary knowledge advances over time and teaches pupils about the similarities and differences between each science.
- Pupils are not expected to acquire disciplinary knowledge simply as a by-product of taking part in practical activities. Disciplinary knowledge is taught.
- Scientific processes such as observation, classification or identifying variables are always taught in relation to specific substantive knowledge. They are not seen as generalisable skills.

Organising knowledge within the subject curriculum

Summary

> A high-quality science curriculum not only identifies the important concepts and procedures for pupils to learn, it also plans for how pupils will build knowledge of these over time. This starts in the early years. Research shows that high-quality science curriculums are coherent. This means the curriculums are

> organised so that pupils' knowledge of concepts develops from component knowledge that is sequenced according to the logical structure of the scientific disciplines. In this way, pupils learn how knowledge connects in science as they 'see' its underlying conceptual structure. Importantly, this sequencing pays careful attention to how to pair substantive with disciplinary knowledge, so that disciplinary knowledge is always learned within the most appropriate substantive contexts.

Sequencing substantive knowledge

There are several reasons why pupils may find learning science difficult.[footnote 81] These difficulties stem from the intrinsic nature of science – that is, the abstract and counter-intuitive nature of scientific knowledge and its use of language – as well as the limited capacity of human working memory.[footnote 82] An individual's working memory capacity correlates strongly with their performance in science.[footnote 83] Pupils with little prior knowledge are particularly susceptible to working memory limitations because they do not yet have the necessary conceptual frameworks to filter out what matters from what does not.[footnote 84]

This means that careful curriculum design, where new knowledge is broken down into meaningful components and introduced sequentially, can support all pupils to learn scientific concepts. This includes those with special educational needs and/or disabilities (SEND).[footnote 85] Danili and Reid showed that performance in chemistry could be significantly improved by redesigning teaching materials.[footnote 86] This involved using carefully selected analogies and presenting knowledge in steps. Importantly, this study did not alter what chemistry was taught and pupils' performance did not vary between teachers. Rather, improvements in learning were likely due to changes made to the teaching materials and ordering of content. Similar results have been found in relation to teaching genetics at school.[footnote 87] However, research identifies that many science curriculums present teachers and pupils with an arbitrary collection of topics introduced in an ad-hoc fashion.[footnote 88] Pupils then fail to develop any conceptual frameworks through which to organise and make sense of their scientific knowledge. This means that it is difficult to use and is easily forgotten. Often, this type of curricular thinking identifies interesting things for pupils to do without rigorous scientific content.[footnote 89]

Curriculum coherence: building conceptual frameworks

Top-achieving countries in TIMSS use the principle of 'curriculum coherence' to organise their national science curriculums.[footnote 90] This involves teaching topics – and the substantive content within them – in a particular sequence that reflects the hierarchical structure[footnote 91] of the scientific disciplines.[footnote 92] Research from the United States suggests that this curriculum journey needs to start in the early years when pupils are introduced to a wide range of vocabulary and phenomena.[footnote 93] This is because there is a clear relationship between young children's general science knowledge and their later science achievement. If gaps in pupils’ knowledge are not addressed early on, evidence suggests that these will continue into secondary school and beyond.

As pupils progress through the science curriculum, new knowledge gets systematically integrated into pre-existing knowledge. This forms larger concepts and new ones, which in turn allow pupils to operate at more abstract levels.[footnote 94] For example, pupils will integrate their knowledge of mass and volume into their concept of ‘density’. In this way, new knowledge depends on what pupils have already learned. Indeed, results from a 12-year longitudinal study show that early introduction to science concepts in primary school positively influences subsequent science learning throughout secondary school.[footnote 95] As these pupils progressed through school, they had fewer and fewer misconceptions compared with pupils who did not do the intervention.

Schmidt, Wang and McKnight found that strong curriculums began with teaching a few of the most fundamental topics of science, such as classification of matter.[footnote 96] These topics remained for the duration of schooling and were added to. This enables important scientific concepts to be revisited and built on over prolonged periods of time.[footnote 97] Importantly, revisiting did not involve repetition of previously taught knowledge. This was expected to be remembered. Instead, it created the opportunity for new knowledge to become part of an emerging conceptual structure, which deepened over the period of schooling. For example, a separate study found that repeated exposure to the concept of energy, spaced out over years rather than weeks, was associated with a deeper understanding of it.[footnote 98] This was because knowledge learned in one unit could be built on and revised in subsequent units, in a range of contexts. By using more than one context in this way, pupils can learn to distinguish between the deep structure of the discipline and the task-specific features.[footnote 99]

Sequencing disciplinary knowledge within the most appropriate substantive contexts

Like substantive knowledge, evidence suggests that disciplinary knowledge should be articulated and sequenced in the curriculum. This supports progression of important disciplinary concepts[footnote 100] and procedures.

Sequencing disciplinary knowledge needs to first take account of its hierarchical nature (for example, teach variables before validity) and then the progression of substantive knowledge. This is because certain substantive concepts provide a better context to learn certain disciplinary knowledge than others.[footnote 101] For example, the particle nature of matter provides an excellent context for pupils to learn aspects of disciplinary knowledge about scientific models. Evolution would not be the best substantive context to teach pupils how to design experiments.[footnote 102] This means that a high-quality science curriculum will identify the best substantive contexts to teach specific disciplinary knowledge.

Once disciplinary knowledge is introduced, it should be practised in different topics and disciplines. This allows pupils to learn how the same disciplinary knowledge is used in different substantive contexts.[footnote 103] For example, knowledge of the concept ‘variable’ can be used alongside substantive knowledge when pupils draw graphs to reveal scientific laws such as Hooke’s Law, or when planning an experiment to investigate how light affects the rate of photosynthesis. In this way, disciplinary knowledge is not forgotten but is built on.

Coherence between mathematics and science

As well as seeking coherence within and between the scientific disciplines, pupils need to make relevant connections between knowledge from other subject disciplines, for example between mathematics and physics.

Subject leaders and teachers of mathematics and science should work together to understand how and when knowledge taught in their respective subjects is similar and different.[footnote 104] Where there are good reasons for differences, it is important that these are made clear to pupils, including any rationale for this. Pupils will then be clear on what knowledge to use and when. It is also important that teachers do not assume that pupils can easily transfer their learning from mathematics to the science classroom.[footnote 105] Pupils will need to be taught how to use mathematics in science.

Importantly, research shows that there is an asymmetry in the dependence between school science and mathematics.[footnote 106] This means that science is dependent on mathematics, but the opposite is not true. Collaboration between departments should therefore not be taken for granted by leaders because mathematics teachers have less to gain than science teachers.[footnote 107] Strong support from senior leadership teams is therefore necessary to make sure collaboration takes place when subject leaders create and refine curriculum plans.

Based on the above, high-quality science education may have the following features

- In the early years, pupils are introduced to a wide-ranging vocabulary that categorises and describes the natural world. These words are not too technical but provide the ‘seeds’ for developing scientific concepts that will be built on in later years.
- Attainment targets, specification points and the EYFS educational programmes are broken down into their component knowledge.
- Substantive knowledge is sequenced so that pupils build their knowledge of important concepts such as photosynthesis, magnetism and substance throughout their time at school.
- Knowledge is sequenced to make the deep structure of the scientific disciplines explicit. This allows teachers and pupils to see how knowledge is connected.
- Disciplinary knowledge is sequenced to take account of:
  - its hierarchical structure

    - the best substantive contexts in which to teach it.
- Once disciplinary knowledge is introduced, it is used and developed in a range of different substantive contexts.
- Planning for progression takes account of what is taught in other subjects. For example, the science curriculum should be coherent with what is taught in mathematics. Where there are differences, these are made explicit to pupils and teachers.

Other curricular considerations

Summary

> Curricular design needs to consider other factors, beyond coherence, that research has identified as being important for enabling progression in science. For example, evidence shows the importance of practice when learning science. Practice makes sure that learned knowledge is accessible and not forgotten. Pupils also need to learn about the different ways that scientists engage in their work through reading, writing, talking and representing science. There is also evidence from research into scientific misconceptions that suggests they can be addressed and pre-empted by changing what is taught and when. This includes making sure pupils are aware of the limitations of models and shortcuts.

Time in the curriculum for consolidation

A curriculum that includes time for extensive practice will help pupils to consolidate knowledge before moving on to new content. This involves pupils repeatedly solving problems that increase incrementally in complexity and receiving feedback.[footnote 108] This ensures that knowledge becomes more accessible over time, which frees up pupils' working memory capacity. Eventually, this allows pupils to engage in more complex problem-solving tasks.[footnote 109]

Consolidation of knowledge takes time. The curriculum therefore needs to not just take account of when new component knowledge is introduced, but also ensure that there is sufficient time for this knowledge to be practised and securely remembered in long-term memory.

Practical procedures, such as using microscopes or heating apparatus, should also be practised regularly so that pupils do not forget what they have learned.

Reading, writing, talking and representing science

To learn about science, pupils need to learn about the different ways in which scientists engage in their work: through reading, talking, writing and representing science.[footnote 110] This is called disciplinary literacy. It is not the same as teaching generic literacy strategies needed to interpret any text. Instead, it involves pupils learning how individuals within a discipline 'structure their discourses, invent and appropriate vocabulary and make grammatical choices'.[footnote 111]

Research shows, however, that pupils are routinely expected to pick up knowledge of disciplinary literacy implicitly.[footnote 112] By defining explicitly in the curriculum what aspects of disciplinary literacy pupils need to know, and why, pupils can be made aware of the aspects of literacy that are peculiar to science. For example, pupils will need to learn how to read and write in the passive voice and learn that many words have multiple meanings depending on context, for example 'cell' and 'model'.[footnote 113]

Misconceptions and the curriculum

Some substantive concepts are more difficult to learn because the scientific knowledge conflicts with everyday knowledge.[footnote 114] Often, these concepts are from subject areas rich with sensory experiences that pupils encounter outside of the classroom. For example, Newtonian mechanics and heat and temperature are concepts where, despite careful instruction, pupils frequently maintain their misconceptions. For example, many pupils (and adults) think that objects require a force to keep moving or that insulating cold items will warm them up.[footnote 115]

These misconceptions are not just 'errors' because they are functional in everyday life and so get reinforced. For example, shops sell plant food, even though plants make their own food through photosynthesis. Misconceptions can also form pervasive barriers to learning science because they compete with the scientific idea in pupils' minds.[footnote 116]

Research shows that experts are better than novices at suppressing misconceptions, as opposed to not having them.[footnote 117] The implications of this for curriculum design are twofold. First, pupils will not only need to know why a scientific idea is correct, they will also need to know why their misconception (prior knowledge) is scientifically wrong. This will require pupils to take a metacognitive perspective at times, where they reason about their concepts.[footnote 118] Research suggests that drawing on previous conceptions from the history of science is helpful here.[footnote 119] This allows pupils to see how their initial conceptions mirror those of early scientists. Second, pupils will need repeated opportunities in the curriculum, in a range of contexts, to practise activating the scientific conception while suppressing the misconception. This can involve exposing pupils to specific 'conflicts' once the scientific conception has been learned.[footnote 120]

If a misconception is challenged too early – before pupils have a scientific conception – it is likely they will rely on the misconception to make sense of the problem.[footnote 121] This may unintentionally consolidate the misconception that teachers were trying to subvert. For example, when pupils with low prior knowledge were presented with a refutation narrative about the day/night cycle, they mistakenly identified the misconception as factually correct information.[footnote 122] These mistakes were less likely when pupils had high prior knowledge.

When the gap between pupils' prior knowledge and the scientific concept presented is too large, pupils are likely to ignore information or generate new misconceptions.[footnote 123] It is therefore important that the curriculum builds pupils' knowledge incrementally, including all the intermediate steps. This should take account of existing conceptions pupils bring to school. The curriculum should also identify which substantive concepts pupils are likely to hold misconceptions in. It is then possible to assign extended curriculum time and specific content to teach those concepts.[footnote 124]

The curriculum itself can also be a source of misconceptions. This is because the order in which knowledge is taught can increase or decrease their likelihood. For example, many pupils consider that the world is made from solids, liquids and gases, as opposed to being made from different substances such as gold or carbon dioxide, each of which can be a solid, liquid or gas.[footnote 125] This is because many curriculums start by focusing on the particle theory in relation to solids, liquids and gases and not substances. This misconception then increases the likelihood of other misconceptions forming, for example many pupils go on to reason that gases, such as oxygen, do not have a mass.[footnote 126]

Using shortcuts and teaching models is another source of misconceptions. For example, many pupils taught the octet rule in chemistry go on to use this shortcut to incorrectly explain why specific chemicals react.[footnote 127] In science, pupils can be introduced to formula triangles to rearrange a simple formula without any knowledge of how it works.[footnote 128]

The problem is not necessarily the use of models or shortcuts in science, rather the curriculum should identify their limitations and their strengths so that pupils learn when they can and cannot be used. This includes making sure that pupils know that scientific models and teaching models are not an exact copy of reality, and that you can have more than one model for the same phenomenon.[footnote 129]

Based on the above, high-quality science education may have the following features

- Sufficient curriculum time is allocated for pupils to embed what they have learned in long-term memory through extensive practice before moving on to new content.
- The component knowledge pupils need in order to read, write, represent and talk science is identified and sequenced.
- Curriculum plans consider how component knowledge introduced at one point in time influences future learning. This ensures that knowledge builds incrementally from pupils' prior knowledge and so pupils' misconceptions are less likely.
- The curriculum anticipates where pupils are likely to hold misconceptions. These are explicitly addressed, and pupils learn how the misconception is different to the scientific idea.

- Pupils know when and why models and rules can be used in science, which includes knowing what they can and cannot be used for.

Curriculum materials

Summary

The implementation of the intended curriculum can either support or undermine its coherence. Evidence suggests that quality textbooks, when used well, have a particularly important role to play in creating a coherent learning progression. They can also free up teachers' time. In contrast, resources that focus teachers' attention on activities, rather than on the underlying content, are not associated with positive science achievement.

Online resources and their (unintended) consequences

Curriculum materials, such as textbooks and worksheets, play an important role in implementing curriculum intent. The quality of these resources, and how they are used, can either support or undermine curriculum coherence.[footnote 130] For example, there is a growing trend of using websites to provide curriculum resources.[footnote 131] Websites usually include only smaller units or activities, meaning that a fully resourced curriculum will likely use resources from many different places. This is likely to disrupt curriculum coherence. All resources need to be carefully matched to curriculum intent, though the easy availability of online resources means that subject leaders should take extra care to ensure that they are not used in a piecemeal fashion.

Science kits

Science is taught using science kits in some primary schools and early years settings. These kits help teachers and pupils do experiments and other enquiry activities.

However, 2 systematic reviews suggest that using science kits is not associated with positive achievement in science.[footnote 132] This contrasts to positive effects for programmes that did not use kits but instead provided teachers with professional development that aimed to improve their science teaching generally. Slavin and others suggest that this may be an unintended consequence of science kits encouraging teachers to be too activity-based, rather than developing the underlying scientific concepts the activities were designed to teach.[footnote 133]

Textbooks

There is evidence that some textbooks in England have become narrowly linked to examinations[footnote 134] and can be a source of misconceptions.[footnote 135] However, high-quality science textbooks fulfil several valuable roles in supporting pupils' learning.[footnote 136] For example, they can give clear delineation of content with a precise focus on key concepts and knowledge. They also provide a coherent learning progression within the subject.

Unfortunately, using textbooks has wrongly become associated with undermining teachers' professionalism and autonomy. Research from the 2011 TIMSS survey found that textbook use in England's schools, as a basis for instruction, is extremely low (Year 5: 4%; Year 9: 8%) compared with other high-performing countries such as Singapore (Year 5: 68%; Year 9: 52%) and Finland (Year 5: 94%; Year 9: 78%).[footnote 137] High-quality textbooks can also free teachers up to spend more time planning and adapting what they are going to teach.[footnote 138] They can also be a valuable source of subject knowledge for inexperienced teachers or those teaching outside of their subject area.[footnote 139]

Based on the above, high-quality science education may have the following features

- Online resources match what the curriculum is intending pupils to learn and are not a source of errors/misconceptions.
- If science kits are used, they help achieve the curriculum intent and the activities themselves do not become the curricular goal.
- High-quality textbooks are used as an important resource for learning and teaching science.

Practical work

Summary

Practical work forms an important part of a science education. This is because it introduces pupils to the objects, phenomena and methods of study. However, research identifies that practical activities are often carried out with insufficient attention to their purpose. This means that it is often unclear whether a specific practical activity is helping pupils to learn a concept or whether it forms a goal of instruction. Evidence suggests that high-quality practical work has a clear purpose, forms part of a wider instructional sequence and takes place only when pupils have enough prior knowledge to learn from the activity. High-quality practical work is therefore dependent on a well-sequenced curriculum that specifies what pupils are learning and builds on what came before.

The purpose of practical work in relation to curriculum content

At its heart, science involves the study of the material world. Practical work[footnote 140] therefore forms a fundamental part of learning science[footnote 141] because it connects scientific concepts and procedures to the phenomena and methods being studied.

However, the specific purposes of practical work in school curriculums are not always clearly defined.[footnote 142] This means that discussions around effectiveness are sometimes confused and not particularly productive.[footnote 143] And although pupils enjoy practical work,[footnote 144] research suggests that this does not, by itself, foster long-term personal interests in the subject.[footnote 145] Indeed, teachers can often prioritise ‘wow’ moments without clear reference to any curricular goal.[footnote 146]

An important first step of effective practical work is to clarify its role in relation to specific **curriculum content**. This means defining whether the practical activity is carried out in order to help pupils to learn substantive or disciplinary knowledge or whether it is a curricular object in itself. For example, pupils may add sugar to water to help them learn substantive knowledge of dissolving. In this case, the concept of dissolving, and not the activity, was the goal. However, it may be that the activity itself is the goal. For example, pupils need to learn how to use a thermometer or how to carry out a specific type of scientific enquiry.

The distinction between pedagogy and curriculum is crucial when thinking about the purposes of practical work because it clarifies what the goal of instruction is, which in turn informs how the practical is completed and assessed.

Practical work to help pupils learn substantive knowledge

Millar outlines 5 related, but distinct, purposes of practical work in helping pupils learn substantive knowledge.[footnote 147] These are set out below in table 2, along with our own examples.

Importantly, he stresses that practical work should form ‘part of a broader teaching strategy’. This means that there needs to be sufficient time after or before the practical for pupils to interpret and explain the observations and measurements made, or that are about to be made.

Table 2: Millar’s different ways in which practical work can help pupils learn substantive knowledge

Purpose	To help pupils to…	Example of curriculum intent
1	Identify objects and phenomena	Materials such as glass, wood and metal; 2 magnets moving apart

Purpose	To help pupils to…	Example of curriculum intent
2	Learn a fact	Pure water boils at 100°C, salt dissolves in water but not oil
3	Learn a concept	Osmosis
4	Learn a relationship	Hooke's Law
5	Learn a model or theory	Brownian motion as evidence for the particle theory of matter

Practical work and disciplinary knowledge

Millar also identifies that practical work plays an important role in teaching specific disciplinary knowledge.[footnote 148] Often, this involves learning to use laboratory apparatus to carry out specific procedures, or about specific aspects of scientific enquiry.[footnote 149] At times, pupils will need to carry out their own scientific enquiries, so they can learn about the often dynamic and unpredictable aspects in which scientists work,[footnote 150] such as the challenges with measurement.[footnote 151]

For this to be successful, sufficient curriculum time needs to be allocated to teach underlying substantive and disciplinary knowledge first.[footnote 152] This is because carrying out a scientific enquiry requires knowledge of the concepts and procedures to guide what is done and why.[footnote 153] If this prior knowledge is not available, pupils will be participating in discovery learning, and **not** scientific enquiry.

Practical work through teachers' use of demonstrations

Teachers' demonstrations play an important pedagogical role in helping to teach scientific knowledge.[footnote 154] They allow pupils to encounter the objects they are learning about while minimising the distractions associated with handling apparatus and recording data. They can also be quick to set up and allow teachers to draw pupils' attention to specific features. For example, there is considerable evidence that the control-of-variables strategy can be taught effectively using demonstrations without hands-on or virtual learning tasks.[footnote 155]

Another study found that pupils who watched teachers' demonstrations outperformed those who watched video and reading interventions.[footnote 156] The authors suggest this effect was partly due to the high-quality questioning that took place.

Similar findings about the importance of teachers' questioning and quality talk, during or after practical work, have been reported elsewhere.[footnote 157] These further support Millar's view that effective practical work must form part of a wider instructional strategy.[footnote 158]

Practical work and objects of study

When planning for pupils to encounter the objects they are learning about, either through teachers' demonstrations or whole-class practical work, teachers need to take account of the distinct and varied nature of each discipline. For example, there are concerns in biological education that there is a zoo-centric focus[footnote 159] and that pupils do not encounter the full range of living organisms in the classroom (such as fungi, protists, bacteria and plants).

Disciplinary encounters should take pupils beyond their everyday experiences. This should not be restricted by an over-cautious approach to health and safety, which can limit the range of practical work.[footnote 160]

Neither should these encounters be restricted to just making science relevant. They should also reveal phenomena that pupils have never encountered before. This includes meeting the national curriculum requirement that science must be taught in the laboratory, in the field and in other environments.[footnote 161] By doing so, pupils learn a more authentic perspective of science[footnote 162] – that science is not just done in laboratories.

Challenges of practical work

The potential of practical work to support pupils to learn scientific knowledge is not always realised. Abrahams and Millar found that practical work often involves pupils following cookbook-style 'recipes'.[footnote 163] Although pupils could remember what they saw and did, there was little evidence that the practical activities helped pupils to learn the curriculum content, either immediately after the lesson or over a longer term. When questioned about why they carried out a specific practical procedure, many teachers simply referred to it being part of a scheme of work.

One important finding from this research was that many teachers held an inductive, 'discovery-based' view of learning. This meant they thought that scientific ideas would emerge simply by carrying out the practical. This has been dismissed previously on both cognitive and epistemological grounds.[footnote 164] That is, pupils will not arrive at the scientific conception that took scientists hundreds of years to develop. The authors instead suggest that pupils need to have the scientific knowledge introduced before the practical so they can link theory to observation. This is especially important when practical work is being used in connection to purposes 3 to 5 in Table 2.[footnote 165] In these purposes, pupils learn abstract ideas that they can only make sense of if they already have extensive substantive knowledge. Other studies have found similar challenges with using practical work in primary schools.[footnote 166]

Research is therefore clear that it should **not** be assumed that pupils will acquire abstract, and often counterintuitive, ideas simply by taking part in a practical activity. Rather, practical work should form just a part of a wider instructional sequence and pupils should have sufficient prior knowledge to learn from the activity.

Based on the above, high-quality science education may have the following features

- The curriculum is sequenced so that pupils have the necessary disciplinary and substantive knowledge to carry out practical work successfully and learn from it.
- The purpose of practical work is clear in relation to curriculum content so that practical activities can be set up and managed to develop pupils' disciplinary and/or substantive knowledge.
- Practical activities form part of a wider instructional sequence that gives pupils time to connect theory to observation.
- Pupils are not expected to learn disciplinary knowledge only through taking part in practical work – disciplinary knowledge should be taught using the most effective methods.
- Pupils encounter the full range of objects and phenomena they are studying through both laboratory and fieldwork. These encounters should take pupils beyond their everyday experiences to develop a sense of wonder and curiosity about the material world.

Pedagogy: teaching the curriculum

Summary

In our overview of research underpinning the education inspection framework (EIF), we identified teaching as the single most important factor in schools' effectiveness. Teacher effectiveness is particularly important in science given the abstract and counterintuitive nature of many of the ideas being learned. Research highlights the importance of teacher explanations in science that build from what pupils already know. These explicitly focus pupils' attention on the content being learned. This often involves the use of teaching models and analogies to represent abstract concepts in a concrete way. Evidence shows that unguided 'discovery' approaches are not effective. Instead, pupils learning science benefit from systematic teaching approaches that carefully scaffold their learning. Because research shows a strong positive relationship between reading achievement and science achievement generally, schools that prioritise pupils' reading will likely help pupils to learn science and vice versa.

Teacher-directed instruction

Analysis of pupil responses and outcome data from PISA 2015 reveals that teacher-directed science instruction is positively associated with science performance in almost all countries.[footnote 167] Teacher-directed instruction (as defined by PISA) involves the following:

- the teacher explains scientific ideas
- a whole-class discussion takes place with the teacher
- the teacher discusses our questions
- the teacher demonstrates an idea

Quality teacher instruction is not lecturing and should not be associated with 'passive learning'. It involves clear teacher explanations alongside a range of questioning and carefully planned activities. Indeed, teaching that adapts science lessons in response to pupils' difficulties is also strongly correlated to pupils' performance.[footnote 168]

Clear teacher explanations form an important part of teacher-directed instruction.[footnote 169] Indeed, pupils report that 'explaining things well' is the most important thing that science teachers do to help them learn.[footnote 170]

Teacher explanations and worked examples[footnote 171] should make connections between knowledge explicit to pupils.[footnote 172] This may include using carefully selected analogies and models[footnote 173] to help pupils link changes at the macroscopic and tangible levels to microscopic and submicroscopic levels.[footnote 174] This is known as relational understanding. For example, teaching pupils about the nature of chemical knowledge helps them to connect what happens at the macroscopic level to the submicroscopic level involving particles.[footnote 175] This prevents pupils from confusing macroscopic changes with submicroscopic changes – say, thinking a decrease in the size of a piece of metal is due to the 'shrinking' of particles. In biology, relationships between the different levels of organisation, such as organs and organisms, need to be made explicit too.[footnote 176]

Technology can play an important role in helping pupils to learn abstract scientific concepts. This can be through animations, simulations and videos when used as part of teachers' lessons.[footnote 177]

Enquiry-based teaching

Before we explore the evidence relating to enquiry-based teaching, it is important to stress that enquiry-based teaching, which is a pedagogy, should **not** be confused with scientific enquiry as a curricular goal, or with practical work generally.

Enquiry-based teaching involves pupils acquiring substantive and/or disciplinary knowledge through exploration. This involves simulating the scientific enquiry process so that pupils develop their understanding of concepts using methods similar to professional scientists.[footnote 178] These enquiry methods are commonly assumed to be ‘best practice’ in science education.[footnote 179] However, the level of scaffolding can vary greatly.[footnote 180]

There are a number of significant challenges for learning science through exploration when you are a novice learner with little prior knowledge. When solutions to scientific problems are actively withheld from pupils, they must search for solutions themselves.[footnote 181] This carries a heavy extraneous cognitive load. This ‘load’ is further increased if pupils also manipulate apparatus. This explains why participating in ‘discovery learning’, in the absence of any guidance or sufficient prior knowledge, does not foster progress.[footnote 182] This approach has long been recognised as problematic in science education.[footnote 183]

Studies into the effectiveness of guided, enquiry-based instruction have reached very different conclusions.[footnote 184] A controlled experimental study found that pupils’ conceptual understanding of substantive science concepts was similar in both scaffolded enquiry and direct instruction.[footnote 185] In contrast, 4- and 5-year-olds learned better when explicit teaching was provided before completing practical activities about floating and sinking.[footnote 186] Similarly, withholding answers before an investigation on light meant pupils reasoned significantly worse than those pupils who had been taught what to expect beforehand.[footnote 187]

The contradictions on the effectiveness of enquiry-based teaching described above are perhaps unsurprising considering the different ways that these approaches are defined and evaluated in the literature.[footnote 188] The lack of consensus on effectiveness means that teachers need to be cautious if they decide to use guided enquiry. This is especially important given the limitations of working memory[footnote 189] and the general finding that pupils with lower levels of scientific literacy consistently report the highest frequencies of enquiry-based activities.[footnote 190] And while research identifies that enquiry-based teaching approaches are positively associated with pupils’ enjoyment of science and their other science-related dispositions, such as interest, so too are teacher-directed approaches.[footnote 191]

There are also specific challenges associated with enquiry-based teaching approaches, beyond cognitive overload,[footnote 192] that pose ‘significant difficulties’[footnote 193] for novices learning science. First, pupils typically record measurements that conflict with the scientific idea. Second, if pupils record valid data, they often lack the necessary knowledge to draw valid conclusions. Third, it is intellectually dishonest to ask pupils to ‘discover’ when the answer is already known. Pupils know this and so it often leads to frustration.

Reading, writing and talking in science lessons

There is strong correlational evidence to show that reading achievement is associated with science achievement generally.[footnote 194] Research suggests that any school approach that improves pupils’ reading will, in turn, help pupils to learn science and vice versa.[footnote 195] Reading well-written scientific texts helps pupils familiarise themselves with key vocabulary and the conceptual relations between these words that form explanations.[footnote 196]

Younger pupils who cannot yet read will learn vocabulary when teachers discuss it and present it to them.[footnote 197] This might be through listening to storybooks and non-fiction texts, as well as rhymes and poems. This is made even more effective when key vocabulary and meanings are introduced through explicit teaching approaches alongside shared book reading.[footnote 198] For example, teachers may focus on specific words before, during and after reading a storybook. This sequence is then repeated during a second reading of the book. Picture books can also help young pupils learn accurate scientific information. A study involving 4- and 5-year-olds showed that picture books were effective in teaching them about falling objects. Pupils learned that heavier objects do not fall faster than lighter objects, despite many pupils starting with this misconception.[footnote 199]

Pupils need opportunities in lessons to recap and to orally rehearse and structure their thoughts, using scientific language. This is important in helping them to use scientific language clearly and precisely. Young pupils benefit from using talk to rehearse their text before they write it.[footnote 200] Through structured writing and speaking, pupils retrieve and reorganise their knowledge[footnote 201] as they communicate their mental representation of a scientific idea. For very young pupils, this might include labelling diagrams.

Based on the above, high-quality science education may have the following features

- Activities are carefully chosen so that they match specific curriculum intent.
- Teachers use systematic teaching approaches, where learning is scaffolded using carefully sequenced explanations, models, analogies and other representations to help pupils to acquire, organise and remember scientific knowledge.
- Teaching takes account of the limited working-memory capacity of their pupils when planning lessons.
- Pupils are not expected to arrive at scientific explanations by themselves without sufficient prior knowledge.
- Systematic approaches, alongside carefully selected texts, are used to teach the most important vocabulary in science.
- Pupils have regular opportunities in the early years and primary classrooms to learn vocabulary through story and non-fiction books, rhymes, songs and oral rehearsal.

Assessment

Summary

> Evidence shows that, despite the best curriculum and teaching, pupils will learn different things from what was intended. This means that teachers need to frequently check pupils' understanding to identify 'gaps' and misconceptions. This must be coupled with subject-specific feedback, so pupils know how to make progress in learning the science content. A second role of assessment is to prevent pupils from forgetting what they have learned. This is known as the testing effect. Research shows that when pupils retrieve knowledge from memory, over extended periods of time, this increases the likelihood that it will be remembered. A third role of assessment is to check that pupils have reached specific curricular goals. This is known as summative assessment and must be carefully used to ensure that its high-stakes nature does not lead to curriculum narrowing and/or increase unnecessary burden on staff and pupils.

Assessment for learning: formative assessment

Formative assessment involves providing feedback for teachers and pupils[footnote 202] that is then used to improve teaching and learning.[footnote 203] One study found that formative assessment in science is most effective for pupils when it is embedded within a lesson sequence, occurring at the same time as new knowledge is taught.[footnote 204] In this way, teachers can see whether the pupils have learned and can remember important component knowledge. If not, teachers can give feedback.

Formative assessment can also be used to find out whether pupils retain and use specific misconceptions. Distractor-driven assessment tools can be especially helpful, such as multiple-choice questions that present pupils with both the scientific conception and misconception.[footnote 205] This is because misconceptions are not always identified in questions that assess general science content.[footnote 206] Evidence suggests that multiple assessment probes should be used, over extended periods of time and contexts, when making claims about learning.[footnote 207] This is because pupils regularly show variability in which conceptions they use when first learning a scientific concept.

Teachers' content knowledge influences their ability to evaluate pupils' ideas and the feedback they give. For example, one study found that teachers with lower scores in their science exams did not include science content in their evaluations of pupils' answers.[footnote 208] Their feedback instead focused on pupils' writing skills or on using tricks for remembering the content and not on pupils' understanding. This failed to provide pupils with useful subject-level feedback. On the other hand, teachers with higher content knowledge evaluated their pupils' answers in relation to their own scientific content.

Assessment as learning: the testing effect

Assessment as learning draws on the cognitive principle that pupils are more likely to remember knowledge if they practise retrieving that knowledge over extended periods of time. This is known as the testing effect. It involves pupils recalling information successfully from long-term memory into their working memory.

To be most effective, research shows that retrieval practice should always be followed with feedback so even incorrect answers can be correctly retrieved in the future. Each retrieval practice should take place over extended periods of time. [footnote 209]

There are now some studies showing the success of this approach in science classrooms.[footnote 210] They show that young children benefit from guided retrieval practice.[footnote 211] For example, adding knowledge to partially completed concept maps was more effective than free recall.

Despite the evidence supporting retrieval practice, teachers need to pay careful attention to 'what' they are asking pupils to retrieve. It must be focused on the right details and not 'destroy[ing] the shaping of content that makes it memorable'. [footnote 212]

Assessment of learning: summative assessment

Summative assessment identifies whether specific curricular goals have been achieved. It therefore plays an important role in evaluating the impact of the curriculum. In science, it consists of assessment of substantive and disciplinary knowledge, including pupils' ability to carry out specific practical procedures and investigations.

Concerns have been raised that high-stakes summative assessments have unintentionally distorted the way that science is taught in schools. This has been particularly problematic regarding practical work in the past.[footnote 213] Our own research into the curriculum found that changes to GCSE assessment coincided with new GCSE content being taught in key stage 3.[footnote 214] Although incorporating some aspects of GCSE content earlier may support progression, these curricular decisions must be based on facilitating progression. They should not be test preparation.[footnote 215] The overuse of exam questions narrows the curriculum and pedagogy. It focuses attention on exam questions, rather than on the body of knowledge that these were designed to test.[footnote 216] A consequence is many pupils end up 'mimicking' the mark scheme. They should instead be developing a deep and lasting knowledge of the scientific concepts.

Summative assessment can also influence whole-school priorities because of its role in schools' accountability measures.[footnote 217] There is concern, from organisations such as the Wellcome Trust[footnote 218] as well as Ofsted,[footnote 219] that removing external science assessments (SATs) in 2009 made schools narrow their curriculum to focus on mathematics and English. This resulted in a decline in the status of primary science.

At the same time, there are indications that teacher-assessed grades at key stage 2 are over-inflating pupils' achievement in science. In 2018, just 21.2% of Year 6 pupils were estimated to be performing at the expected standard in science according to national sample assessments.[footnote 220] This contrasts with 82% of pupils according to teachers' assessments.[footnote 221] This discrepancy may be because some schools do not give enough time or training for moderation, which are both necessary to ensure that teachers' judgements are valid and reliable. [footnote 222] It may also be due to the different methods used. For example, teacher assessment in primary schools is frequently based on classroom work, whereas national science sampling tests measure pupils' ability to remember and apply substantive and disciplinary knowledge.

Another unintended consequence of assessment, if used inappropriately, is that it can contribute to teachers' workloads. This could be through excessive marking, excessive feedback or excessive data-recording requirements.[footnote 223] Secondary science teachers are particularly at risk of excessive workload demands due to the number of examination papers that pupils complete.

Based on the above, high-quality science education may have the following features

- Teachers and pupils are clear on the purpose of assessment. There is clarity about what is being assessed.
- Assessment is not overly burdensome on teachers' time in relation to marking, recording or feedback.
- Feedback is focused on the science content and not on generic features. Teachers have sufficient subject knowledge to be able to do this.
- Pupils regularly retrieve knowledge from memory to help them remember and organise their knowledge. This is coupled with feedback. Teachers think carefully about what pupils are being asked to retrieve and whether this prioritises the most important content.
- Overuse of external assessment items, such as GCSE or A-level questions, is avoided because this narrows the curriculum and leads to superficial progress that does not prepare pupils for further study.
- Systems are in place to support teachers to make accurate decisions when assessing pupils' work. This includes supporting primary teachers with statutory teacher assessment of science at key stages 1 and 2.

Systems at subject and school level

Summary

> A high-quality science education depends on effective subject and school leadership. This starts with allocating sufficient curriculum time to teach the science curriculum. However, research shows this does not always happen, particularly in primary schools. It is also paramount that leaders ensure that

> science teachers and technicians have access to regular, high-quality subject-specific continuous professional development (CPD). This is especially important in science given that many teachers are teaching outside of their subject specialism. Although research shows that schools face challenges retaining science teachers early on in their career, these challenges can be at least partly addressed at a leadership level. For example, leaders can adjust teachers' timetables to prioritise teaching fewer groups and subjects. Finally, pupils need access to sufficient resources so that they can carry out practical work, both in the classroom and field. This should be in appropriately sized groups, which better enable first-hand experiences.

Teachers' knowledge and expertise

Shulman identified the importance of both content knowledge and pedagogical content knowledge to teacher education.[footnote 224] Pedagogical content knowledge is important because it allows teachers to transform their 'content knowledge' into something that pupils can learn from. Although we think about content knowledge and pedagogical content knowledge separately, the latter depends on the former.[footnote 225] Content knowledge is therefore at the heart of expert science teaching.[footnote 226]

Despite its importance, science teachers often have insufficient content knowledge. This includes 'specialist' teachers with degrees in their subject who still need to learn 'school science', as well as how to teach it.[footnote 227] Weak content knowledge is not only a barrier to clear explanations, it is also a source of pupils' misconceptions in science because teachers may also hold these same unscientific ideas.[footnote 228] One study, for example, reveals that many primary school teachers have the same scientific misconceptions as their pupils.[footnote 229] The majority of primary teachers in this study thought gravity increased as objects increase their height above the ground. A third believed all metals were magnetic.

Expecting teachers to pick up subject knowledge through time spent teaching is misguided.[footnote 230] It is therefore important that teachers have access to high-quality subject-specific CPD.[footnote 231] This needs to be focused on the content and how to teach it, as opposed to generic pedagogies[footnote 232] and so should be aligned with the curriculum that teachers teach.[footnote 233] CPD should also aim to improve science teachers' disciplinary knowledge in relation to the nature of science[footnote 234] and its methods,[footnote 235] as well as how to carry out practical work.[footnote 236] Importantly, research suggests that teacher education needs to take an explicit and reflective approach to teaching teachers about the nature of science and its methods.[footnote 237] It should not be assumed that teachers will have learned about the nature of science simply as a consequence of having taken part in science-related activities.[footnote 238]

Subject-specific CPD is important for all science teachers and teaching assistants.[footnote 239] But it is especially important for non-specialist primary teachers. This is because estimates suggest that just 5% of primary school teachers hold specialised science degrees and teaching qualifications in science.[footnote 240] This means that some do not feel confident in teaching science. This is a concern given that a recent randomised control study showed improved teachers' confidence was a repeatable predictor of pupils' improvement when teaching about evolution at primary school.[footnote 241]

It has been suggested that an important first step in developing primary science expertise is for every primary school to have at least one teacher who specialises in teaching science.[footnote 242] This recommendation is supported by findings from the Wellcome Trust's study into primary science leadership.[footnote 243] This identified that science leaders need dedicated leadership time.

The professional bodies such as the Institute of Physics, Royal Society of Chemistry and Royal Society of Biology, as well as teacher associations like the Association for Science Education, also have important roles to play by ensuring that their members have access to professional development.[footnote 244]

Teacher retention

Science teachers are more likely to leave their school and the profession compared with non-science teachers.[footnote 245] This is particularly the case for newly qualified teachers (NQTs). The odds of them leaving the profession within 5 years is 20% higher than for non-science NQTs. This may be because science teachers are more likely to teach multiple subjects, which increases their workload, or because they can earn more outside of the profession. Given the shortage of chemistry and physics teachers entering the profession,[footnote 246] it seems imperative that schools and other organisations not only improve recruitment but do everything possible to improve retention.

A recent report for the Gatsby Charitable Foundation identified 8 recommendations for schools to increase the quality and quantity of science teachers.[footnote 247] These include:

- reducing workload through careful timetabling (discussed further below)
- using science-specific CPD
- using instructional coaching
- paying science teachers more to reflect their outside earning potential

School timetabling

Careful timetabling plays a significant role in reducing science teachers' workload and developing expertise. This is because many science teachers are routinely teaching outside of their specialism. Allocating a higher proportion of a teacher's timetable to their subject specialism can reduce their workload and increase opportunities to develop their subject expertise. Workload can also be reduced, especially during the early stages of a teaching career, by assigning teachers specific key stages or reducing the number of year groups they teach.[footnote 248]

Where teachers do teach just some groups, they must still be well acquainted with the curriculum for all year groups so that they can take account of prior knowledge[footnote 249] and not repeat content unnecessarily.

Having insufficient time to teach the curriculum is another cause of teachers' stress. A recent analysis of timetable models in England revealed that, in some secondary schools, science receives a low share of teaching time compared with optional GCSEs.[footnote 250] This is supported by recent international comparison data that shows pupils in Year 9 received considerably less curriculum time for science in England's schools than the international average.[footnote 251] At primary, a shortage of curriculum time for teaching science has also been identified as a particular concern.[footnote 252] This often happens when science is 'squeezed out' of the primary curriculum due to an over-focus on English and mathematics.[footnote 253]

The importance of technicians and practical resources

Technicians provide a crucial role in supporting high-quality practical work in schools. However, research shows that not all schools have enough science technicians.[footnote 254] Indeed, schools in areas of higher social deprivation tend to be worst affected.

Like teachers, technicians benefit from specialising. In average-sized secondary schools, there should be technicians to support practical work in biology, chemistry and physics.[footnote 255] Technicians should also have regular CPD opportunities. These lead to direct improvements in the quality of practical work in the classroom.[footnote 256]

As well as access to technical support, effective practical work requires adequate practical resources. Adequate here refers to the type, condition and quantity of equipment. Previous research suggests that not all primary or secondary schools have the resources they need.[footnote 257] At secondary level, biology is the poorest resourced science. Our 2013 science subject report found that in some schools, pupils are required to complete practical work in large groups.[footnote 258] This means that not all pupils gain first-hand experience of taking part in the procedures and practices that they are learning about. In the most severe cases, shortages of practical equipment will prevent pupils from accessing the intended curriculum.

Based on the above, high-quality science education may have the following features

- Teachers, teaching assistants and technicians have access to high-quality subject-specific CPD to develop subject knowledge and pedagogical content knowledge. This is aligned to the curriculum.
- In primary schools, there is at least one teacher who specialises in teaching science and science leaders have dedicated leadership time.

- Science teachers engage with subject associations, and take responsibility, with support from the school, for developing their own subject knowledge throughout their career.
- Early-stage teachers in particular have timetables that allow them to develop expertise in one science and that do not give them too many key stages to teach.
- Timetables allocate appropriate teaching time to science, reflecting its status as a core subject in the national curriculum. There are particular concerns that pupils in some primary schools are not receiving sufficient curriculum time to learn science.
- Pupils have access to sufficient practical resources to take part in demanding practical work, either independently or in appropriately sized groups that enable first-hand experiences.

Conclusion

This review has explored a range of evidence relating to high-quality science education. It has drawn on research from many different countries and organisations. It also builds from the same research base that underpins the EIF.

In this conclusion, we have identified some general principles. Each principle is not restricted to a specific area of science education, such as curriculum, pedagogy, assessment or school systems. Rather, we have chosen them because evidence presented in this review suggests that they play a central role in influencing many aspects of science education that lay the foundation for subject quality.

The first principle concerns the nature of the scientific discipline itself. **A high-quality science education is rooted in an authentic understanding of what science is.** This recognises science as a discipline of enquiry, underpinned by substantive and disciplinary knowledge, that seeks to explain the material world. Importantly, this requires that pupils learn about the differences between each science. This includes learning about the diversity of approaches used to establish knowledge in science and knowing that there is not one scientific method. When the discipline is not well understood, evidence shows that this leads to superficial curriculum thinking and ineffective pedagogical approaches. Often, these focus on developing ill-defined skills. They also confuse scientific enquiry as a curricular goal with enquiry-based teaching approaches. Without a strong sense of the discipline, it is also easy for high-stakes assessment, either through its absence or presence, to distort what is taught.

The second principle extends from the first. It reflects the important status of scientific concepts, and the relationships between them, as building blocks of scientific knowledge. **A high-quality science curriculum prioritises pupils building knowledge of key concepts in a meaningful way that reflects how knowledge is organised in the scientific disciplines.** This starts in the early years. Importantly, this assumes there is enough curriculum time to teach science. Evidence shows that this is not always the case.

Historically, science education has looked mainly to pedagogy to address the difficulties pupils face learning science. However, as seen throughout this review, by changing what pupils learn it is possible to prevent some of these difficulties from arising in the first place. For example, the effectiveness of practical work can be increased by making sure that pupils have the necessary prior knowledge to learn from the activity. Similarly, by changing what pupils learn, and when, the likelihood of misconceptions forming can be reduced. The science curriculum is therefore more than a description of the journey towards expertise. It is also the means by which to get there. **This means that science curriculums should be planned to take account of the function of knowledge in relation to future learning.**

Together, these 3 principles show that a high-quality science education carefully balances several competing priorities/tensions. For example:

- pupils learn that science is a body of established knowledge but is also a discipline of enquiry
- complex concepts and procedures must be broken down into simpler parts, but knowledge must not become fragmented or divorced from the subject discipline
- curriculum is distinct from pedagogy, but what you learn is influenced by how you learn it

To navigate these tensions successfully, teachers and subject leaders require in-depth knowledge of science and how to teach it, as well as an understanding of how pupils learn. Building teachers' knowledge is therefore a central plank of high-quality science education. The evidence in this review suggests that this knowledge should be developed in relation to the curriculum that is taught.

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