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The Case for Inquiry-based Science Education (IBSE)

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Published in November 2021.

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Acknowledgements

IAP is grateful to the reviews and comments provided by members of the IAP Science Education Global Council (https://www.interacademies.org/education/governance) on earlier drafts of this report.

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Inquiry-based teaching in science (IBSE) has for some time been widely advocated by major international bodies due to its potential, not only to raise levels of students' scientific knowledge and understanding, but also to help them develop skills and attitudes needed for life in the 21st century. Despite well-argued support and adoption in many countries, however, there is a lack of convincing research evidence of the positive impact of IBSE. Indeed, its effectiveness has been challenged by widely publicised findings of the Programme of International Student Assessment (PISA) 2015 survey of 15-year-olds (OECD, 2016).

The purposes of this paper are to bring together currently available research evidence and reasoned arguments for adopting inquiry-based pedagogy in science education and to identify factors that may support or inhibit the implementation of IBSE. It considers the benefits to students as individuals and to the community of which they are members – particularly to societies in need of more scientists, engineers and technologists – and draws together implications for science education policy and practice.

Section 1 concerns the meaning of inquiry, conveyed in national and international documents, where there is an abundance of titles used for different inquiry-based programmes ('learning by doing', 'discovery learning', 'hands-on learning' etc). The combination of knowledge and skills, that is a defining feature of the process of learning through inquiry, is illustrated using a model of inquiry-based learning. This represents visually how the use of scientific inquiry skills (predicting, hypothesising, collecting and interpreting data, drawing conclusions) leads to development of scientific knowledge and understanding.

Section 2 is also concerned with clarifying the concept of IBSE but goes beyond the formal language used in definitions of inquiry as a generic pedagogic strategy. Examples of inquiry, one from a secondary school class and one from a primary school class, are used to describe what is going on in classrooms, in terms of what students and teachers are doing and what students are learning, when IBSE is in action. It should go without saying that these examples should be seen only as an indication of how some aspects of IBSE might be put into practice. They certainly do not represent the complexity of IBSE, which will always be manifested in different ways and with different inputs from the teacher, summarised in the list of teachers' and students' activities in sections 2.2 and 2.4.

The first two parts of Section 3 discuss the case for inquiry-based pedagogy having a key role in science education. The aims of learning science are expressed in terms of the development of scientific literacy – a general ability to engage confidently with scientific aspects of the world, for instance in making decisions about food, exercise, use of energy and care for the environment. The scientific knowledge that this involves goes beyond familiarity with scientific facts and principles. Scientific understanding also encompasses knowledge of the skills and procedures through which content knowledge is built from evidence (procedural knowledge) and knowledge of the nature and development of scientific knowledge, including understanding that ideas and explanations may need to be revised in the light of new evidence (epistemic knowledge). Whilst content knowledge can be learned through direct transmission, what is needed for developing knowledge of procedures and the nature of science is provided by the experience of and reflection on inquiry-based experiences.

Section 3 also discusses how the benefits of scientific literacy can be made available to all students through their science education, whether or not they continue to study science beyond school. A 'curriculum for all', has the potential to motivate more students to continue study of science beyond school. This would go some way to mitigating concern, in both developed and developing countries, that not enough young people, particularly girls, are choosing to seek careers in science, technology, engineering and mathematics (STEM) disciplines.

Section 4 addresses the question most often asked of IBSE and, indeed, of other pedagogical approaches, as to whether it 'works' in the sense of resulting in improvement in students' learning. Answers to this question draw on findings from empirical research into the impact of IBSE on students' learning, on arguments based on current understanding of how learning takes place and on what studies of the brain (neuroscience) add to reasons for learning through

inquiry.

The first part of Section 4 describes the procedures and findings of nine research studies of different design and focus, which report on the impact of IBSE on students' learning. In most cases the results are inconclusive, with any changes in learning attributable to IBSE being small and subject to considerable measurement errors. Given the impact on education policy of the findings of PISA surveys, particular attention is given to the results of the 2015 PISA survey that are a challenge to advocates of inquiry-based teaching. Data from a students' questionnaire administered as part of the 2015 PISA survey, were used to identify the extent of students' experience of various teaching approaches. Correlations between PISA scores and students' experience of inquiry-based or teacher-directed pedagogy resulted in a negative relationship between students' scores on PISA tests and frequency of experience of inquiry-based teaching, and a positive relationship with teacher-directed instruction. The findings need to be critically interpreted, noting that the information on teaching concerned only quantity, not quality, of inquiry teaching and was supplied by students who are likely to have understood the questions in different ways. Pisa was not set up to compare pedagogic practices and correlational evidence does not establish causal relationships. There are many questions left unanswered by these findings, highlighting the need for more, and more appropriately designed, research to address them.

Following the empirical research studies in the first part of Section 4, the second part turns to arguments from two other fields of research that are increasing our understanding of learning and have implications for inquiry-based learning: theory of learning and neuroscience. Developing understanding through inquiry, accords with a view of learning as a process in which learners make sense of new experience by using their existing ideas; that is, a constructivist view of learning. But current views of learning go further, recognising that learning is not just an individual matter but involves social interaction with others in which understanding is developed in a manner described as socio-constructivist. This view of the process of learning underpins the value of the discussion, dialogue and argumentation around evidence that are integral to learning through inquiry.

The expanding knowledge of the structure and function of the brain and of links between what happens inside the brain and response to events outside are of particular interest in improving teaching and learning. Studies of the role of memory in learning have particular importance for inquiry-based education and the avoidance of 'cognitive overload' when there are many things to attend to, as in tasks such as planning and conducting investigations. The load can be reduced by providing help with some aspect of the process of inquiry, as in various forms of 'guided inquiry'.

The research studies in Section 4 bring to light several factors, drawn together in Section 5, that have the effect of restricting or even inhibiting implementation of IBSE. Some of these are related to how inquiry-based learning is described and interpreted in practice; others are pre-existing circumstances that conflict with what is needed to support IBSE, including an overloaded curriculum that encourages teachers to rush through activities with not enough time for inquiry. Policies relating to assessment and accountability, and established expectations of teaching and the role of teachers can also inhibit implementation of IBSE. Other factors are linked to the resources available for IBSE including not only materials and equipment for practical science, but also teachers' pedagogical knowledge and ability to help students develop and use inquiry skills.

Section 6 complements Section 5 by revisiting the potential obstacles and considering possible action through which they might be reduced or even surmounted. Some suggestions are found in the studies which raised the problems in the first place; others emerge from research and practical examples of successful implementation. The changes needed are the basis of the recommendations for policy and practice in Section 7.

1. The concept of IBSE

Before setting out, in later sections, reasons for adopting IBSE and considering the evidence of its impact on learning, it is important to be clear about its meaning. An agreed definition is important to bring clarity in the discussion and avoid misunderstandings, to which IBSE is particularly prone. But it is necessary to go further than definitions to understand how components of IBSE combine to improve learning in science. A model of learning science through inquiry is used to explain how inquiry can lead to development of ideas and knowledge of scientific aspects of the world around (content knowledge), while the experience of using inquiry skills in this process enables students to develop awareness of the role of inquiry skills (procedural knowledge) and the understanding of the nature of science (epistemic knowledge).

1.1 Defining inquiry-based science education

Descriptions of inquiry occur in various curriculum documents and classroom materials and have undergone subtle changes, at times laying emphasis on different aspects of the process. The US National Research Council's *Science Education Standards* of 1996 laid stress on the use of inquiry skills, defining inquiry as involving:

> "making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known; using tools to gather, analyse and interpret data; proposing answers; explanations and predictions and communicating the results." (NRC, 1996: 23)

The later *Framework for K-12 Science Education* (NRC, 2012) instead of using the term 'skills' describes the activity of engaging in scientific investigation in terms of 'practices' in order to emphasise that

> "engaging in scientific inquiry requires coordination both of knowledge and skills simultaneously". (p41)

It cannot be stressed enough that a key feature of learning through inquiry is the combination of these two aspects. This having been said, the discussion here uses the term 'skills', interpreted in this wider sense, as in the definition developed through work by the IAP in the course of many different projects in various countries:

> "IBSE means students progressively developing key scientific ideas through learning how to investigate and build their knowledge and understanding of the world around. They use skills employed by scientists such as raising questions, collecting data, reasoning and reviewing evidence in the light of what is already known, drawing conclusions and discussing results. This learning process is all supported by a pedagogy that allows students to learn through inquiry " (adapted from IAP, 2010:5)

Emphasis on different parts of this definition have given rise to a plethora of terms used to describe new approaches to science teaching and learning that involve some aspects in common with IBSE. Box 1 lists some of the most commonly used terms with a brief note about the focus of each. In this document they are all treated not as different from but as aspects of IBSE.

Box 1: Terms used in describing teaching and learning approaches in science

Many of these terms have been created or adopted to contrast with teacher-directed approaches. They are now best regarded as sub-components of inquiry-based education rather than being competing approaches.

Active learning: recognises that students are the ones who do the learning and so must be actively constructing learning rather than passively receiving it.

Discovery learning: suggests that students learn mainly from their own inquiries and not directly from the teacher.

Learning by doing: focuses on students being physically active in manipulating materials so that they see things for themselves.

Hands-on learning: similar to 'learning by doing' emphasises the value of physical activity.

Minds-on learning: emphasises the need for students' thinking in making sense of their experiences and relate new experience to existing ideas.

Process-based learning: used in the 1970s to emphasise the use of scientific skills (replaced by inquiry-based learning).

Student-centred learning: a general term contrasted with teacher-centred instruction where the learning experiences are closely controlled by the teacher.

Evidence-based learning: emphasises the search for and use of evidence in developing understanding. (This is distinct from evidence-based education, meaning teaching methods for which there is evidence of effectiveness in bringing about intended learning).

Project-based learning: emphasises the transfer of learning to new situations; often involving working on complex tasks over a period of time and culminating in a real product or an event such as a presentation.

Problem-based learning: similar to project-based learning. Students work in small groups to tackle a realistic problem, involving identifying what learning is needed for the solution.

Competence-based learning: identifies the outcomes of inquiry-based education in term of learning practices and processes that contribute to scientific literacy.

1.2 Inquiry in science education: past and present

Inquiry is by no means a new concept in education; it has been consistently valued over the years. Its roots can be found in the recognition of importance of children having an active role in their learning appearing in the writings of educators such as Homer Lane (1875-1925), Dewey (1870-1952) and Montessori (1870-1952), drawing on the earlier ideas of Rousseau (1712-1778), Pestalozzi (1746-1827), and Froebel (1782-1852). These educators were concerned with a general approach to education which respected the role of children's curiosity, imagination and urge to interact and inquire. This approach was not specifically related to learning science, which in any case was not regularly included in primary school education until well into the twentieth century. However, the special relevance of inquiry for learning science was noted by educators who advocating the introduction of science into the primary school curriculum in the 1950s and 1960s.

1.3 Inquiry across the curriculum

Inquiry (or enquiry – alternative spelling, but the same meaning) is a term used in daily life, referring to seeking explanations or information by asking questions, using knowledge from experience and seeking for evidence. Within education some inquiry skills can be used in other subject domains, such as mathematics, technology, history, geography and the arts, as well as science. In each domain there is knowledge generated. In the case of scientific inquiry this is knowledge and understanding of the natural and made world around.

Inquiry is not the only approach used in mathematics and social subjects, of course, but neither is it the only approach used in science. There are aspects of science education that involve procedures, vocabulary and facts best learned through direct instruction. However, the development of understanding is something that students cannot receive from others but must generate through their own thinking and actions.

1.4 Some misconceptions of IBSE

Since inquiry-based science often involves physical activity and the manipulation of materials and equipment, it is sometimes treated as synonymous with 'practical work'. This neglects the role of 'minds-on' and the value of discussion and use of secondary sources in learning science. This misunderstanding results in inquiry being viewed as concerned exclusively with developing skills, out of the context of developing knowledge and understanding. Related to this view is the assumption that inquiry is mainly suitable for primary and middle school science where it is assumed, mistakenly, that building key ideas is less relevant than at secondary level. This reflects the reality that it has indeed proved more difficult to introduce inquiry-based activities into secondary school science education (see IAP, 2010). It also reflects the lack of confidence primary teachers often have in their own science understanding.

A further mistaken view is that inquiry means that students 'discover' everything for themselves and should not be given information by the teacher or use other sources. This assumes that students come to new experiences with open minds and develop their ideas by inductive reasoning about what they observe and find through their inquiries. The reality is that students come to new experiences not with empty minds, but with ideas already formed from earlier thinking and experiences, which they use to try to understand the new events or phenomena. To counter these limited conceptions of inquiry-based science it is necessary to look at how understanding is developed through inquiry and the role of inquiry skills in the process.

1.5 A model of learning science through inquiry

Definitions and descriptions of IBSE identify its component parts, but to explain how it results in learning, and why it is important, involves looking at how the parts relate to each other and are combined in the development of knowledge and skills. The process of learning through inquiry is best described with the help of a diagram.

Figure 1 (page 34) depicts the process as starting with a question or problem raised by a new event or experience (a). Through initial exploration and observation, a learner tries to make sense of the new phenomenon using ideas and knowledge from previous experience and may come up with one or more ideas that are thought to be relevant (b). This is a process helped by discussion with others so that the experience brought to bear is greater than that of any individual. One of these linked ideas is selected for testing by being used to make a prediction (c). This is a key part of the process of learning through enquiry, for only if ideas have predictive power are they useful (Hawking, 1988). Evidence is then gathered (d) so that what was predicted can be compared with what happens (e). How this is done will depend on the nature of the problem; it may require careful observation, experimentation, consulting records, looking for patterns in data. There is no single 'scientific method' that applies to problems as different as why the Moon appears to change shape and the colours in a rainbow. Often there is more than one prediction to test and so some repetition of the prediction and collection of evidence loop. A conclusion can then be reached about whether there is evidence to support the possible explanation and the idea on which it is based (f). If the evidence agrees with the prediction, then the initially linked ideas is tentatively accepted as relevant to explaining the new experience and becomes a 'bigger' idea, that is, it explains a wider range of phenomena. Even if there is no agreement, something is learned about the idea applied, for it is just as important to know what doesn't work as what does. In that case, an alternative idea needs to be considered and tested.

1.6 The role of inquiry skills

The arrows in Figure1 are labelled with the actions involved in moving from one point to the next. These actions are the processes (practices) or skills of inquiry. The results of the inquiry will depend on how these actions are carried out, that is, on how well students make a prediction, plan an investigation, interpret data and draw conclusions. The development of scientific ideas is dependent on the collection and interpretation of data being carried out scientific rigour, otherwise ideas that ought to be rejected may be accepted and students' own unscientific ideas persist. It follows that a key part of the pedagogy required to support inquiry-based learning is to help students develop the procedural knowledge and the skills needed in science investigation. This is an important reason for helping students to develop their inquiry skills and to become more conscious of using them.

Helping students to progress in the development of inquiry skills requires a view of what progression in skills means and how it will be recognised and fostered. Harlen and Qualter (2018) have suggested four dimensions of change:

- Being more able to use skills in a range of contexts, including unfamiliar ones.
- Using more elaborated skills; for instance, using instruments for observing details.
- Becoming more conscious of using skills and using them effectively.
- Using reasoning and logic to make sense of experience.

Through the process of inquiry, students can develop knowledge not only of ideas and concepts that help to explain events and phenomena in the world around, but also knowledge of the procedures of scientific investigation that lead to reliable outcomes and knowledge about the nature of science. These three kinds of knowledge are described as content knowledge, procedural knowledge, and epistemic knowledge.

2. Inquiry in action

The formal language used in defining inquiry as a generic pedagogic strategy that can be applied in the investigation of many different questions and problems, does not adequately convey what it means in practice. This Section provides real examples of inquiry: one from a secondary school class and one from a primary school class. These and other instances of inquiry in practice are then used to describe what is going on in classrooms when IBSE is in action in terms of what students and teachers are doing. How such inquiry activities enable students to develop knowledge of scientific ideas, of how science 'works' and of the nature of science is also indicated.

2.1 Examples of inquiry-based learning

There can be an infinite number of different situations and events in which students learn through inquiry and a variety of forms of inquiry. Although not possible to illustrate this wide range, it is nevertheless useful to have specific situations in mind when discussing the actions of teachers and students when involved in IBSE, recognising that the examples in Box 2 are neither typical nor unusual.

Box 2: Examples of inquiry in action

Example A (extracted from Hadfield (1995) quoted in Rönnebeck (2018))

In the laboratory, the teacher directs the students, working in small groups, to use tongs to hold a small piece of copper foil in the Bunsen flame. When the copper is red hot, they place it on a ceramic mat and allow it to cool. The teacher asks them to describe what they see and to think about the black layer formed on the copper. They propose several explanations (hypotheses): that the black layer is soot from the Bunsen flame (recalling that a candle flame can deposit soot on objects); that it is produced from inside the copper when heated; that it is a reaction of the copper with the air around. Groups then plan an investigation to test one of these hypotheses. They predict that if the black comes from the flame then if the copper is heated without direct contact with the flame then there would be no black layer. The students produce a plan for an investigation to see what happens and, when satisfied that it can be done safely, they conduct the investigation. They discuss what the result tells them about the idea that the flame was the source of the black layer and decide whether to test one of the alternative explanations.

Example B (based on Harlen, 2015)

This inquiry started from the students' common experience of finding that when they take a can of cold drink out of the fridge the surface of the can becomes wet. The teacher asked them for their ideas about what the moisture was and how it got there. To investigate the phenomenon in the classroom and test some of their ideas, the teacher suggested using a can without a top in which they could put different liquids and could be cooled by putting ice inside. Most students thought that the moisture on the outside came through the metal from the liquid inside. When they tried with no liquid but only ice inside there was still water on the outside, which they thought was from the melting ice and made a plan to test this. Other ideas were suggested and tried but none gave convincing results. They were searching for other ideas when a student noticed that he could make the cold surface mist up by blowing his breath on to it and they turned to considering that the air around might have something to do with it.

2.2 What students are doing

These glimpses of classroom activities provide specific examples of what students are doing when involved in inquiry and in the actions represented in figure 1. Each point alone is of no particular significance but taken together they show how IBSE is distinctly different from conventional science instruction. A comprehensive list of what students are doing would include:

- raising questions, identifying problems and considering how they might be investigated;
- engaging in exploring events and objects – often, but not always, manipulating materials

and using equipment;

- working in collaborative groups in which students share and construct ideas together;
- proposing possible explanations based on their previous experience and using these hypotheses to make predictions;
- developing plans for investigations to test predictions;
- conducting investigations, collecting data by observation and experimentation as appropriate and recording results;
- drawing conclusions from the results about the ideas being tested, and communicating what they have done and found;
- reflecting on the process of inquiry and on any changes in their ideas.

2.3 What students are learning

It is worth noting that in the examples in Box 2 the students were fully engaged in the activity and, importantly, did not know the answer to the problems in advance. This contrasts with a good deal of traditional 'practical work' in science where students are told what to do and what they are to find. Genuine inquiry engages students' interest and thinking, leading to learning with understanding using ideas that they have worked out for themselves and made 'their own.'

It is equally important to ask: what are the students learning and how is this facilitated? Although the examples in Box 2 are not intended to represent all kinds of inquiry, of which there are many, but even these short descriptions show how learning of the three kinds noted in Section 1 – knowledge of science content, knowledge of scientific procedures and knowledge of the nature of science – can be developed through inquiry-based activities:

Content knowledge

> In example A the series of tests that the students devised allowed them to eliminate some of their hypotheses and to identify contact with air as important in explaining the black film on the copper. When brought together with other experiences of change in substances, these observations lead to the realisation of the 'big idea' that some substances can combine with others to form a new substance. In example B the investigations of these younger students led to the emergence of awareness of the existence of water vapour in the air and conditions in which it changes from gaseous to liquid. This contributes to the big idea that at room temperature, some substances exist as solids, some as gases and others as liquids.

Procedural knowledge (how science 'works')

> The students in these examples have experience of discussing possible explanations (hypotheses) and using ideas from previous experience to make predictions. Through making plans for testing their own ideas, they experience what is involved in planning includes deciding what data to collect, how to collect it and to make sure that fair comparisons are being made where appropriate. They experience at first-hand how to record results systematically in various ways and what is involved in interpreting results and drawing conclusions. Reflection on these experiences, with the support of the teacher, helps students to identify how this way of working contributes to their learning and understanding of the nature of scientific activity.

Epistemic knowledge (the nature of science)

> Through reflection on how they have developed their ideas students can identify what it is that makes an activity one of scientific investigation, with especial reference to the important role of evidence. Recognising that ideas based on evidence may have to be changed when there is conflicting evidence, contributes to the big idea that scientific explanations and theories are those that best fit the evidence available at a particular time.

2.4 What teachers are doing

The students' experiences and activities that lead to the learning just outlined are significantly dependent on the teacher. The teacher's role is essential, not only in providing the material, learning environment and resources, but in asking the students questions that provoke their thinking and inquiry skills. Questioning is one of the most important features of teachers' practice affecting students' opportunities for developing their understanding and inquiry skills. It is also one of the aspects of teachers' practice that can most easily be made more effective for learning (Black et al, 2003). By changing the form and timing of their questions, teachers can elicit students' ideas, provoke their thinking and encourage use of inquiry skills. Questions expressed in personal terms ('what do *you think* might be the reason for the black film on the copper?' rather than 'what *is* the reason') are more likely to give access to what students really think. Questions can specifically encourage use of inquiry skills such as planning ('what do you need to do to find out if it is something to do with the air?') or prompt reflection ('what does this tell you about the explanations that you can get from scientific investigations?').

Students will not arrive at new ideas merely through their own thinking and action. They need access to a range of ideas that are different from their own. So, an important part of the teacher's role will also be ensuring that students have access to sources of information, alternative ideas to test out and the materials and equipment needed. It is often helpful for the teacher to provide 'scaffolding' (see also Section 6.2) to help students consider an idea or action that is not their own but that they can try out to make their own. Fellow students are an important source of different ideas, which is why promoting dialogue through dialogic teaching (Alexander, 2012, 2020) is important to IBSE.

In summary, if students are to do the thinking and learning involved in inquiry, teachers' activities will include:

- providing materials, equipment and access to sources of information for students to use and help in using them;
- facilitating group work and collaborative learning, by arranging space for group discussion and working and encouraging students to share and listen to each other's ideas;
- asking open questions that elicit students' ideas and encourage the use of inquiry skills;
- encouraging dialogue and talk in which students develop and extend their understanding;
- asking students to make predictions and plan investigations, helping where necessary to ensure that the planned actions are safe and productive;
- providing a supportive environment for students' investigations, listening to them and taking their ideas seriously;
- scaffolding alternative ideas that could help students explain the results of their investigation;
- encouraging students to reflect on what they have found and how they found it.

3. The role of inquiry in science education

Following from the last two sections on the meaning and nature of inquiry, this section presents reasons for inquiry taking a key role in science education pedagogy. It argues the case for the aims of science education being expressed in terms of the development of a scientifically literate population and provides a rationale for an important role for inquiry pedagogy in achieving this. It identifies the importance for individual students of inquiry-based science education as a key part of their preparation for life, and the value for society when citizens have the knowledge and skills that can be developed through IBSE. The role that ICT can have in this development is acknowledged. This is followed by considering what can be done about the shortage of scientists, technicians and engineers being experienced by both developed and developing countries across the world.

3.1 Promoting scientific literacy and scientific competence

There is more to understanding in science than knowledge of facts, concepts and theories that help in explaining the world around (content knowledge). As widely recognised (OECD, 2016; EC, 2007), it also encompasses knowledge of the skills and procedures through which content knowledge is used in building and refining models based on evidence (procedural knowledge) and understanding of the nature and development of scientific ideas, including the need to revise ideas and explanations in the light of new evidence (epistemic knowledge). These three aspects reflect three of four strands of scientific proficiency described by Duschl et al, 2007; the fourth being participating productively in scientific practices and discourse.

These outcomes are the foundation of what is commonly expressed as 'scientific literacy' (Millar and Osborne, 1998). A closely related term, 'competence,' is used to describe "the ability to successfully meet complex demands in a particular context" (Rychen and Salganik, 2003: 43). The goals of competence-based learning in science, as for scientific literacy, go beyond a knowledge of science. They include familiarity with the nature of scientific activity and the ability to evaluate claims and arguments, reflected in the PISA description of a scientifically literate person as able to:

- "Explain phenomena scientifically – recognise, offer and evaluate explanations for a wide range of natural and technological phenomena.
- Evaluate and design scientific inquiry – describe and appraise scientific investigations and propose ways of addressing questions scientifically.
- Interpret data and evidence scientifically – analyse and evaluate data, claims and arguments in a variety of representations and draw appropriate scientific conclusions." (OECD 2016a: 20)

3.2 The role of inquiry in the development of scientific literacy

In today's world, where science and technology play increasingly important roles, society needs a population that is scientifically literate and able to make decisions about aspects of their daily lives that are of benefit both to themselves as individuals and to society. A key question to be faced, then, is how to work towards the learning outcomes required for scientific literacy; in other words, what experiences should science education provide to help students develop the three aspects of scientific knowledge?

> Content knowledge has been the predominant focus of science education throughout its history, building a body of knowledge which has been passed from one generation to another, mainly through direct teaching. Whilst there is some conceptual learning involved in all three types of knowledge needed for scientific literacy, knowledge alone is insufficient for the development of procedural and epistemic knowledge.
>
> Procedural knowledge is clearly related to action, to 'doing' and knowing how to 'do'. But it is not enough to experience doing something to learn how to do it. Knowledge of a skill, whether it concerns physical or mental action, requires some reflection on the experience and the part that the 'doing' played in developing understanding.
>
> Epistemic knowledge, similarly, cannot be directly transmitted to learners. It requires

reflection on, and experience of, scientific activities, as well as knowledge of how scientific ideas and explanations have changed.

What is needed for developing these aspects of scientific literacy, is to be found in the description of the activities identified in the definition of IBSE in Section 1 and in the actions of students and teachers listed in Section 2. This provides a rationale for the role of inquiry in science education in terms of its contribution to developing a scientifically literate population of people who know how science works and are able to take part in meeting major challenges facing humanity in providing sufficient water and food, controlling diseases, generating sufficient energy and adapting to climate change (UNEP, 2012).

Individuals frequently make decisions about matters that affect their health, food, well-being, use of energy and care of the environment. As well as impacting on their own daily lives, such decisions have wider implications for their own and others' future well-being. They do not require everyone to become a scientific expert but to be able to make informed choices which affect their environment and their wellbeing. As such, the skills and understanding developed through IBSE are central to young people's preparation for life.

Understanding how science is used in many aspects of life enables students to appreciate the importance of science and the appropriate use of scientific ideas. Students need to know how, both currently and historically, the use of scientific knowledge in engineering and technology, can impact both positively and negatively on society. Furthermore, education in science has a unique role in creating understanding, and the will to tackle, the issues that lead to inequalities in wealth, employment, health and education across the world (IAP, 2015:6). Important benefits at the national level follow from young people developing the knowledge and understanding that enable them to make informed choices about, their diet, exercise, use of energy and care of the environment. What is good for the health of its citizens is good for the health of a country's economy.

3.3 Using ICT in IBSE

The use of information and communications technologies in general and in education in particular has developed at an increasing pace in the recent years. The unusual circumstances created by the corona virus pandemic are only partly responsible for this; the use, particularly by children, of tablets, smartphones, laptops was already accelerating. In countries where students have access to these devices and to the internet, the use of these technologies can enhance, but does not replace, opportunities for developing the kinds of knowledge and skills discussed in the subsection above. In parallel with the concept of scientific literacy, students and teachers should acquire 'digital literacy', meaning confidently using digital technologies for purposes such as communication, collaboration, raising questions and solving problems.

There are innumerable and increasing ways in which ICT can support learning in science. They include the ability to access evidence needed for students' own investigations, that would otherwise be difficult to collect in the classroom, by using, for instance, data-loggers and sensers. Evidence from other sources, provided by the internet via Google and You Tube videos, enables students to make and test predictions and expand their understanding of phenomena such as relating to the Earth in space. The internet provides many other opportunities to move beyond the classroom through virtual tours of places of interest, and to connect with others to exchange ideas and experiences. The image of students working alone at a computer is no longer appropriate. Instead, they can use their digital devices to share their ideas with others, for instance through making animations, models, PowerPoint presentations or drawings on screen.

There is accumulating evidence of the effect of using ICT on students' performance (Tamim, et al, 2011). However, the effective use of ICT in these ways clearly depends on how teachers incorporate the use of new technologies into their pedagogy. This in turn has implications for teacher education, in particular, for the provision of continuing professional development online.

3.4 A science curriculum for all students

Clearly, the benefits of developing scientific literacy should be available to everyone through their science education. It requires a science curriculum that can truly be described as 'science for all' or 'science for citizenship'; one that is relevant to students' lives regardless of their future occupation or career. But at the same time, science education should provide for the needs of those students who will progress to higher education in science and will become the scientists, engineers and technologists basic to countries' economic and intellectual growth.

How to cater within the same curriculum for both the needs of those who will have careers in science or in science-based enterprises and for those who will not take this route has been a major challenge to curriculum design over many years. Solutions attempted or suggested include: the idea of a 'core plus options'; parallel routes at upper secondary level; and various ways of providing appropriate experiences for these two groups of students.

But the increased emphasis on the importance of everyone having the opportunity to develop scientific literacy, as defined above, points to an alternative approach. This recognises the role of an inquiry-based pedagogy in enabling all students, not just those who will pursue further studies or careers in science and science related subjects, to acquire scientific literacy by the end of their school education.

A curriculum seen as "a course to enhance general scientific literacy" (Millar and Osborne,1998: 9), would be suitable for all students and, as a result, more may be motivated and inspired to take up further study in science and science-related disciplines than is currently the case.

3.5 Increasing participation in science-based occupations

Many governments and economies are concerned that not enough young people are choosing to study science beyond the age of 16. There is also widespread concern that the profile of those who do continue to study science or science-based subjects and take up related careers is too narrow, with women, working-class and some minority ethnic groups remaining under-represented, especially in the physical sciences and engineering. There is also a pressing need to improve the spread of scientific literacy across all societal groups.

Current and predicted gaps in uptake of STEM (science, technology, engineering and mathematics) subjects may impact negatively on countries' economy. Investment in STEM disciplines is increasingly seen in both developed and developing countries as a means of boosting innovation and driving the economy. In Europe, reports from the EC (2004) and Rocard et al (2007) have identified scientific inquiry as a means of improving science teaching and addressing the need for more young people to undertake careers in science and engineering (Rönnebeck et al, 2018). A Manpower Talent Shortage Survey of 2018 showed that the scale of the problem varies considerably among countries and is most pronounced in Asia, Japan being the country most severely affected, with 89 percent of companies reporting STEM skill shortages. China was one of the countries reporting a low shortage rate (13 percent) with the UK only a little higher at 19 percent. (McCarthy, 2019). There is clearly a need to encourage more students to continue to study science in secondary and tertiary education and to choose careers in STEM disciplines.

3.6 Factors affecting choice of a career in science

A research study of how students aged 10-14 view careers related to STEM subjects has thrown some light on the reasons for their choices. The ASPIRES study (Archer et al, 2010) aimed to increase understanding of how young people's aspirations develop over the ages 10-14 years. Using online surveys and repeated interviews of students over five years, plus some interviews with parents, the study explored what influences the likelihood of a young person aspiring to a science-related career. One of the main findings of relevance was that there was no lack of high aspirations shown either by the students or their parents. However, whilst careers in business, managerial, and professional careers, such as in the law, medicine, teaching, or as a celebrity, ranked high in terms of preference, becoming a scientist came much lower than most other careers. The students with more positive views of school science were the most likely to aspire to a career in science, but liking school science was not a major factor in determining their choice of career. Agreeing that interesting things are learned in science and that science is useful did not lead to preferring it to other subjects or wanting to become a scientist.

Factors that did appear to be involved in the choice of career included the role of a student's family 'science capital' (Archer et al, 2015). The concept of science capital relates to a person's science-related knowledge, attitudes, experiences and social contacts. Students with a parent or family friend with a science qualification or occupation, and who discuss science at home, have more science capital than those without such experiences. It was found that those with more science capital were likely to aspire to study of science beyond the age of 16. Another factor was the students' narrow view of the range of occupations which involve science, which was generally restricted to becoming a doctor, teacher or scientist. These occupations were seen as requiring a high level of 'brain power' and so science was seen as being for the 'very bright'. Furthermore, it was found that gender, ethnicity and social class continue to be factors associated with choice. A student who is female, white and with low levels of science capital is the least likely to see herself in a science-related occupation and is most likely to aspire to an art-related or career or employment in the 'caring' industry.

These findings point to actions that may counter the circumstances that deter students from choosing science-based further study and careers. Teachers can help by broadening the view of occupations to which a study of science can lead, showing how science is used in everyday life, referring to role models, and actively encouraging students from under-represented groups to consider science as being 'for them'. Also, and most importantly, "policy-makers might consider promoting embedded models of career education in which curriculum learning is systematically linked to a wide range of real-life careers and occupations" (Archer et al, 2010: 4).

4. Evidence and arguments for IBSE

Does it ‘work’? is the question most often asked by anyone considering implementation of IBSE, or indeed, any innovation in teaching. In this section, answers to this question draw on three main sources of evidence: findings from empirical research into the impact of IBSE on students learning; arguments based on current understanding of how learning takes place; and what studies of the brain (neuroscience) can add to the reasons for learning through inquiry.

4.1 Empirical research

There is now a considerable amount of empirical research evidence relating to the effectiveness of IBSE, in contrast to the position less than 20 years ago. As will be seen, any one study of inquiry-based activity is rarely conclusive, since the impact of the element of inquiry or of any other teaching approach, is bound to be only a small part of students’ experience of science lessons and there are many variables that distinguish one teaching approach from another, few of which can be controlled. So, even though the effect of variables relating to the learning environment, teacher and students may be minimised in the study design, there remain many influences on achievement that mean the effect of element of inquiry, or other teaching approach, is likely to be difficult to detect (Harlen, 2004).

The first part of this Section describes in brief outline the following examples of different types of study:

1. PISA 2015 (association between science performance on PISA tests and teacher-directed and inquiry-based instruction).
2. Inquiry-based teaching and student achievement in GCSE and PISA (PISA data linked to student data in England).
3. Evaluation of an inquiry-based programme in Sweden (NTA) (comparison of NTA and non-NTA students’ performance on national tests and course grades).
4. Evaluation of the LASER model of IBSE (comparison of students receiving LASER intervention with non-LASER intervention using standardised and other tests).
5. Inquiry synthesis project (a systematic review of research which rated studies in relation to the degree of inquiry within each treatment).
6. Inquiry-based laboratory work in higher education (comparison of inquiry-based and ‘cookbook’ laboratory work in a university biology course in the Czech Republic).
7. Gender differences in IBSE impact (research conducted in the Czech Republic to investigate gender differences in secondary school students’ responses to IBSE instruction).
8. 12-year longitudinal study of science concept learning (an historically interesting project that supported the teaching of science to primary age students).
9. Effect of students’ emotional intelligence (study of response to IBSE of students with different emotional intelligence).

4.1.1 PISA 2015

The Programme for International Student Assessment (PISA) is a major source of data about the policies and practices in science education that are associated with achievement in science, mathematics and language. The programme was set up by the OECD to “contribute to an understanding of the extent to which education systems in participating countries are preparing their students to become lifelong learners and to play constructive roles as citizens in society” (OECD, 1999 p7). As well as involving all 36 OECD countries, PISA surveys are conducted in other countries and economies. In 2015 there were over 72 country or economy participants in total. Box 3 gives a summary of main points.

Box 3 The Programme for International Student Assessment in outline

In surveys conducted every three years, PISA assesses the achievement of 15-year olds in three major domains, each described as a 'literacy': reading literacy, mathematical literacy and scientific literacy. The programme's aim is to provide information about the extent to which, by the end of the compulsory years of schooling, students have acquired the skills and understanding in these domains needed for young people to participate effectively in society. Although mathematics and science correspond to school subjects, PISA is not about assessing how well students have mastered the curriculum content, but rather what general skills and broad understanding they have acquired. Thus it is important to distinguish assessing 'scientific literacy' from assessing 'science.' The decisions to focus on scientific literacy is consistent with thinking at the time when PISA was conceived (eg Millar and Osborne, 1998). That is, that the outcomes of science education are development of a general understanding of important concepts and explanatory frameworks of science, of the methods by which science derives evidence to support claims for its knowledge, and of the strengths and limitations of science. These are skills and understandings needed by all students, including those who will study science in depth and will become tomorrow's scientists and technologists.

In this and in several other respects, PISA differs from other international surveys in science and mathematics education. It concerns only 15-year-olds, testing a sample of students of this age at three yearly intervals, beginning in 2000. All three literacy domains are tested in each survey, one being a major and the others minor features of the survey. Scientific literacy has been the major domain in 2000, 2009 and 2015. As well as testing a sample of students, using written tests translated into language(s) appropriate in each country, background information is collected by questionnaires completed by students and school principals. This enables relationships between teaching practices, school characteristics and student achievement to be reported.

It is the information on teaching practices in science lessons, particularly the use of inquiry-based activities, that is the focus of interest here.

In the 2015 PISA survey the student questionnaire included, for the first time, questions about how often they experienced certain events or activities in their science lessons ('never or almost never', 'in some lessons', 'in many lessons', 'every lesson or almost every lesson'). The activities were chosen as indications of the general type of teaching experienced by the students. Four practices were identified: 'teacher-directed instruction', 'perceived feedback', 'adaptive instruction' and 'inquiry-based instruction'. Those questions seen as indicating typical actions and events for one of these practices were combined into an index for that type of instruction. Higher values of this index indicated more frequent use of these strategies. The relationship between using a strategy more frequently and science performance was calculated from the correlation of these two measures.

The PISA report of the 2015 survey gives particular attention to the correlations between science performance on the PISA test and the indices for teacher-directed and inquiry-based instruction. The headline findings were that there was a strong negative correlation between students' PISA score and the frequency of inquiry-based instruction and a positive correlation with frequency of teacher-directed instruction. It appeared that higher PISA scores were associated with more teacher-directed instruction and with less inquiry-based activity.

These findings are a challenge to the advocates of IBSE and the developing international consensus as to its benefits. (e.g. European Commission, 2007; IAP, 2010; Fibonacci Project, 2012). It is important, therefore, to look in some detail at the indices used in the analysis, whilst keeping in mind several points about these measures: that they are based on frequency of certain experiences and not their quality; that they are reported by students, who will interpret the questions in different ways; that correlational evidence does not establish causal relationships; that PISA was not set up to compare pedagogic practices.

The index for teacher-directed instruction was formed from the answers to questions concerning the following four teaching events, with the average percentage in brackets of students in OECD countries who reported that these things happen in their classes in 'almost every' or 'in many' science lessons:

1. The teacher demonstrates an idea (56%)
2. The teacher explains scientific ideas (55%)
3. The teacher discusses our questions (55%)
4. A whole class discussion takes place with the teacher (40%)

For the index of inquiry-based science instruction the results for the following nine questions were combined. The percentage in brackets is the OECD average of students reporting that these things happen in 'most' or 'almost all' science lessons.

1. Students are given opportunities to explain their ideas (69%)
2. The teacher explains how a science idea can be applied to a number of different phenomena (59%)
3. The teacher clearly explains the relevance of science concepts to our lives (50%)
4. Students are asked to draw conclusions from an experiment they have conducted (41%)
5. Students are required to argue about science questions (30%)
6. There is a class debate about investigations (26%)
7. Students are asked to do an investigation to test ideas (26%)
8. Students spend time in the laboratory doing practical work (20%)
9. Students are allowed to design their own experiments (16%)

The higher frequency events concerned students either receiving explanations from teachers or explaining their own ideas. At the lower frequency end, fewer than one in three were engaged in arguing in science or in practical investigations. Only about a quarter of students reported experiencing some of the activities that match the definition of inquiry-based science given in Section 2. The PISA analyses suggest that, for those who do have these experiences, there is a negative correlation with science score. However, for the first three questions, students who reported that these things happened in most or all lessons scored higher than those for whom this never or hardly ever happens.

The report notes the need for caution in interpreting correlational evidence, which does not establish causal relationships. Teachers may have different reasons, for instance, for using hands-on activities, but nevertheless "the arguments against using hands-on activities 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." (OECD, 2016: 71).

In addition to the caution about interpreting correlations, it must be remembered that PISA was not set up to compare the impact of different instructional practices. There is no 'treatment' of some students that made sure that they experienced IBSE whilst others had a different experience. We do not know what aspects of inquiry, if any, students actually experienced. A different design of study is needed to be sure of this, one in which the achievement of students who are known to have experienced IBSE can be compared with those who did not. In other words, this means a research project which ensures that the independent variable – experience of IBSE – is in place when the dependent variable – science achievement – is measured. PISA provides a valid measure of the latter but not the former.

Such controlled research projects are difficult to conduct for several reasons. In any classroom there will be a variety of instructional practices in use, so that the effect of experiencing inquiry will be 'diluted' by other practices to some extent. (The four practices identified in the index of teacher-directed instruction PISA are far from independent of each other as the published intercorrelations show). For findings to be reliable it is also desirable that the practice under study has been in place long enough for teachers and students to be familiar with what is involved.

4.1.2 Inquiry-based teaching and student achievement in PISA and national examinations

Jerrim, Oliver and Sims (2019) used data from the 2015 PISA survey data linked to the National Pupil Database for England, which contains results for each student in national tests and public examinations, to investigate whether guided approaches are positively associated with achievement in science and whether higher frequency of inquiry-based teaching leads to higher levels of achievement. They describe guided inquiry as "maintaining emphasis on students acquiring knowledge indirectly through investigations" whilst increasing the level of guidance provided by the teacher (p36). They present theoretical arguments in favour of 'guided' as opposed to 'pure' inquiry science teaching, drawing on cognitive load theory (Kirschner et al, 2006). This states that learners must process new information in their working memory (see 4.3), which is limited in capacity and overloading can impede learning. Guidance from the teacher or worksheet takes away some of the load of dealing with all aspects of conducting an inquiry.

The outcome measure used by Jerrim et al (2019) initially in their investigation was students' results in the examination taken at the end of secondary education at age 16 (GCSE). The PISA results from the student questionnaire giving the frequency of various activities in their science lessons (see above Section 4.1.1) were used to create a scale of the amount of inquiry-based teaching the students experienced. This was then used to explore the association between frequency (amount) of students' experience of inquiry and their GCSE grades.

The results showed no difference in GCSE grades between those who experienced high levels of inquiry-based teaching compared with those with little such experience. However, students in the middle range of inquiry experience achieved higher grades than those with little or none, although the effect size was extremely small. The researchers investigated the possibility that the GCSE tests may not adequately reflect the outcomes of IBSE by switching to using the PISA test results as the outcome measure, but this did not change the results, confirming their conclusion 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" (Jerrim et al: 42). They consider possible explanations for their null-results in terms of the quality rather than the quantity of inquiry-based teaching. That is, that "teachers in England are (on average) failing to deliver inquiry-based science teaching methods appropriately" (ibid). They also argue that the practical nature of inquiry-based teaching provides students with opportunities for noise and disruptive behaviour that reduces the quality of their learning experiences. Further research that uses measures of the quality rather than only quantity of inquiry-based activity is clearly needed.

4.1.3 Evaluation of an inquiry-based programme in Sweden

The Swedish *Natural Science and Technology for All (NTA)* programme is an adaptation and translation of the programme *Science and Technology for Children (STC)*, which was developed in the USA. Different versions of STC were created in a number of countries eg. Brazil, Croatia, Germany, Korea, Panama, and Thailand, as well as Sweden. The NTA programme, like STC, provides classroom teaching materials in the form of kits and training for teachers. It is in two parts, for younger children in grades K-5 and older students in grades 6-9. The impact of the NTA programme on students in grade 9 during 2009 and 2010 was the subject of an extensive and detailed study by Mellander and Svärdh (2018). At that time NTA was used by about 7000 teachers in a third of Sweden's municipalities, involving a total of about one in eight students in K-9.

National standardised science test for grade 9 students were introduced in Sweden in 2009 and the results were available for Mellander and Svärdh to use in evaluation of the NTA programme. The national test comprises three subject tests, in biology, chemistry and physics. Each student only takes one test, which is decided by the test administering agency, thus avoiding the distorting effect of test practising. Each subject test includes some items relating to content and some to science process skills. As well as scores on standardised tests, other outcome measures used were grades based on the tests and course grades provided by teachers. Using these three measures, a sample of students who had studied NTA was compared with a non-NTA sample. Students were not allocated randomly to NTA and non-NTA but by matching at the individual level on a range of background characteristics. The researchers commented particularly on the importance of care in allocating students to groups since their work shows that a direct, "unadjusted, comparison of participants and non-participants will lead to the erroneous conclusion that the NTA programme has negative impacts on both test results and course grades" (Mellander and Svärdh:36).

In their study of students in grades 6-9, there were positive and statistically significant differences between NTA and non-NTA students in test scores and test grades but not in course grades. The effect sizes varied among the science subjects, were very small and were subject to considerable measurement errors.

A second, similar, study conducted with students in grades 4-6 by Mellander and Rasmusson (2020) when NTA was more firmly established, using a far larger sample (23,000 matched pair instead of 1,000). Measurement errors were considerably reduced and significant effects were found for test grades and school grades for all science subjects and also for mathematics and for technology (course grades only since there were no national tests in technology). Effect sizes corresponding to about 30 % of the distance between two adjacent grades in the A – E interval of the grading scale, were found for all the science subjects, with the largest for biology. Other findings were:

- The NTA effects were around 40 % lower for children with a foreign background than for students with a Swedish background and this difference is statistically significant.
- The longer students participate in the NTA program, in terms of number of semesters, the more they benefit.
- With respect to gender, there were no statistically significant differences. The non-significant tendency for female students to score higher and get higher grades than male students was in line with general trends in Sweden in grades 4-6.
- A particularly important finding related to the professional development of teachers. The effect of NTA on students whose teachers had a formal pedagogical training were twice as large as for those without a formal teaching qualification. However, the NTA effect was not further increased if a teacher with pedagogical training also had formal qualifications in science, technology, or mathematics. The researchers concluded that this has implications for the professional development in the NTA programme, which should make up for lack of pedagogical skills as well as shortcomings relating to science subject matter knowledge.

4.1.4 Evaluation of the LASER model of inquiry-based science education

LASER (Leadership and Assistance for Science Education Reform) is a systemic approach to change, developed by the Smithsonian Science Education Centre in the USA. It provides inquiry-based classroom activities, differentiated professional development, administrative and community support, equipment kits, and help with assessment. "High quality professional development (PD) for science teachers is a central component of the LASER model." (Alberg, 2015:10).

A longitudinal evaluation study of the LASER model, funded by the US Department of Education, was carried out by the Centre for Research in Educational Policy (CREP) at the University of Memphis using a sample spread over three districts (Zoblotsky et al, 2017). The results provided clear evidence of positive impact of inquiry, not only on performance in science but on pupils' reading and mathematics as well.

Students in grades 3-8 were divided into two groups, those receiving the LASER intervention and a comparison group. The 9,000 or so students in the study were followed over three years. Two measures were used in comparing the two groups of students: the elementary and middle school state standardised assessments in reading, mathematics and science; and the PASS (Partnership for the Assessment of Standards Based Science) which consisted of multiple choice, open-ended and hands-on performance tasks.

Findings for the PASS items showed:

- particularly large and statistically significant differences between LASER and comparison students in the hands-on performance tasks;
- some significant differences in the open-ended task scores;
- less difference for the multiple-choice items.

Results for the state standardised tests led to the conclusions that:

- inquiry-based science improves student achievement not only in science but also in reading and mathematics;
- LASER advances student learning compared with non-LASER students, especially among underserved populations including children who are economically disadvantaged, require special education or are English language learners.

Both the open-ended and performance task Sections of the PASS require students to communicate their knowledge in written form and engage in activities associated with critical thinking and problem solving – twenty-first century skills associated with college and career readiness. It is noteworthy that these are the areas of achievement in which LASER students and schools performed well.

The authors add an important observation that, in spite of current rhetoric regarding the need for increased emphasis in K-12 schools on all STEM (science, technology, engineering and mathematics) areas, the pressures associated with standardized tests has greatly decreased the time allocated to science teaching and learning in many public schools. They report that:

> "few schools participating in the current study allocated sufficient time at all grade levels to implement the science units as designed, and in some, science was taught only in the grade levels in which it was tested (usually 5th and 8th grades). Still, multiple positive outcomes were achieved, and much has been learned through this study regarding the potential of the LASER model, and particularly the use of inquiry-based strategies in elementary and middle school classrooms, to prepare students for success" (Alberg, 2015: 11).

4.1.5 Inquiry Synthesis Project

Bringing together the findings from several studies addressing similar questions adds strength to the contribution of anyone study which may contain only some elements of inquiry. Systematic reviews (meta-analyses) follow prescribed procedures in searching for and evaluating the quality of all relevant studies in order to extract the findings supported by the best evidence. Procedures for systematic review have been developed and become widely practised in countries across the world.

The Inquiry Synthesis Project (Minner et al, 2010) was a systematic review of research projects on the nature and effects of IBSE. It was funded by the National Science foundation and conducted by the Education Development Center. It followed the procedures of a systematic review, beginning with a wide-ranging search of the literature for studies meeting criteria of relevance to the research question of the review. The purposes of the study were to determine whether there was an association between the nature or amount of inquiry instruction and student learning outcomes, and whether methodological rigour had a moderating effect on studies' findings (op cit: 482). The researchers identified 138 studies matching the definition of classroom inquiry. Each study was categorised in terms of key aspects of the degree of inquiry in the instructional treatment: student outcomes; research design; and methodological rigour.

The degree of inquiry in the treatment described in each study was judged from the emphasis on student responsibility for learning, student active thinking, and student motivation, in each case being given a rating from 0 (no emphasis) to 4 (a lot of emphasis). Once all of the components of instruction were rated for student active thinking, responsibility for learning, and motivation, the ratings were summed to reflect the overall level of *inquiry saturation* within each instructional treatment. As well as coding the level of inquiry, the researchers developed a coding scheme for the effect of instruction. Six different outcome types were coded: student understanding of science concepts, facts, and principles or theories; and student retention (a minimum of 2 weeks after treatment) of their understanding of science concepts, facts, and principles or theories.

Across all 138 studies in the synthesis just over half showed a positive impact of some level of inquiry instruction. Within the overall number there were 101 studies where the outcome was science conceptual understanding. For these, although the outcome was not significantly associated with degree of inquiry saturation, when broken down to more detailed elements of inquiry, there was a positive association between the amount of active thinking and drawing conclusions from data and understanding science content. Of the 42 studies that involved comparison between treatment and non-treatment students more than half found that students in treatments with higher amounts of inquiry saturation (especially hands-on engagement with science phenomena and emphasis on student responsibility for learning) did statistically significantly better than those in treatments with lower amounts of inquiry. Overall, however, the associations between learning and amount of inquiry saturation were modest.

The researchers acknowledged that

> "The evidence of effects of inquiry-based instruction from this synthesis is not overwhelmingly positive, but there is a clear and consistent trend indicating that instruction within the investigation cycle (i.e. generating questions, designing experiments, collecting data, drawing conclusion, and communicating findings), which has some emphasis on student active thinking or responsibility for learning, has been associated with improved student content learning, especially learning scientific concepts. This overall finding indicates that having students actively think about and participate in the investigation process increases their science conceptual learning" (op cit: 493).

It was also found that more hands-on experiences of phenomena in the natural and made world was associated with increased conceptual learning. Whilst this finding was consistent with constructivist learning theory it was not compatible with the education policy at the time embodied in the 'No child left behind' programme, with its emphasis on development and testing of basic skills. Constrained by state tests, which largely test knowledge or recall of discrete science facts, concepts, and theories, teachers, it was reported, often resort to using less demanding (both for them and students) teaching strategies. But, as Minner et al comment:

> "Ironically, the findings from this synthesis indicate that teaching strategies that actively engage students in the learning process through scientific investigations are more likely to increase conceptual understanding than are strategies that rely on more passive techniques." (ibid)

They also point out the need for better research tools that enable the results of several studies to be brought together to quantify the degree of inquiry and how this relates to learning outcomes.

4.1.6 Study of gender differences in IBSE impact

This study was conducted in Slovakia by researchers from Slovakia and the Czech Republic. It was part of the four-year Europe-based FP7 ESTABLISH programme which, from 2010 to 2014, developed, disseminated and evaluated learning units and teacher education to promote the use of IBSE in secondary schools. The evaluation focused on the impacts on pupils' intrinsic motivation for learning science, understanding the importance of science for society and pupils' epistemological beliefs, in each case asking about any differences between boys and girls.

The results reported here were obtained from students' answers to two questionnaires: Q1 focusing on intrinsic motivation; Q2 focusing on attitudes to science and ideas about the nature of science. Both questionnaires were prepared in versions for lower secondary (12–15 years of age) and upper secondary (16–19 years of age) school students.

Inquiry-based science learning units, developed within the programme, were taught by teachers who had attended a four-day course on IBSE. The students followed instructions in worksheets, whilst the teacher coordinated the students' activities. By asking suitable questions, the teachers promoted student-teacher and student-student discussion. Activities predominantly involved skills associated with planning experiments, collection, processing, analysis and interpretation of data and formulation of conclusions.

Q1 was administered after each learning unit. It was completed by a sample of 1792 upper secondary and 136 lower secondary school students. Q2 was administered before using the IBSE units and again after the end of the project to a sample of 299 upper secondary and 53 lower secondary students.

The students' response to the IBSE activities was positive, finding them interesting, entertaining and useful. Small gender differences were observed in all the three learning outcomes: motivation for learning science, understanding the importance of science for society and epistemological belief, with girls being generally more positive in their evaluation. There was little change in boys' or girls' knowledge of science after the IBSE activities, apart from an increase in girls' curiosity. There were no significant changes in students' attitudes to science, but girls expressed less interest in science and in a career in science in the post-test. In relation to epistemological belief there was change only in relation to items about how scientific findings need to be based on evidence. With very small definite gender differences found, the researchers concluded that the impact on girls of the activities was more positive than for the boys whose attitudes and opinions changed very little after the IBSE activities.

The authors commented that "we expected a more positive impact on students' opinions and beliefs." They go on to describe circumstances that were likely to have influenced the results and need to be taken into account in judging the outcome of the study:

- School reform in Slovakia began in 2008, only two years before the start of this study.
- Whilst the Slovak national curriculum puts emphasis on the inquiry-based approach in the science teaching, there is a lack of supporting materials available to teachers to implement inquiry.
- Slovak teachers are generally not very well trained in IBSE.
- Traditional teaching methods are dominant in schools and preferred by teachers.
- The sample of teachers in this study participated in workshops and were provided with supporting methodological documents, but they still lacked the competences required for IBSE teaching; they tended to answer the questions themselves and to teach the activities directly.
- Students are not used to this approach to teaching and often expect to be provided with help from the teacher or clear instructions on how to process or what to do, in other subjects as well as in science.

The researchers summarised the findings as follows:

> "We believe that these are the main reasons why the results did not indicate more significant changes. To obtain more convincing results, teachers need more permanent and systematic professional development, which will support greater applicability of IBSE in teaching, also in more subjects than those considered here. Still, we can say that the above analysis brought an interesting comparison of girls and boys in the perception of IBSE, showing a more positive impact on girls, who seem to have been more influenced by this form of teaching." (Kekule et al, 2017: 113).

4.1.7 Inquiry-based laboratory work in higher education

Although this study, carried out by Rokos and Zavodska (2020) in the Czech Republic, involved only students in a university biology course, its findings are relevant to school learning, where similar results have been obtained. It compared inquiry-based science education in human biology at the university level with traditional laboratory work using "cookbook" manuals written by teachers. Tests of students' knowledge and scientific skills were used before and after the laboratory work.

During a one-term course students were divided into two groups, learning through inquiry-based (98) and traditional (70) approaches. The meaning of these approaches was expressed using a 5-level model of inquiry by Buck, Bretz, and Towns (2008). This identifies levels of inquiry in terms of how much the activities provide for students the following: a problem to investigate; the theoretical background; step by step instructions for the investigations; a framework for analysing results; discussion of results and conclusions. In the traditional, or cookbook, approach students are provided with the problem, the theoretical background and detailed instructions. When students are required to identify the problem and work out how to investigate it and reach a conclusion this would be described as authentic, or open inquiry.

For content knowledge, the learning of inquiry group learning increased more than that of the control group, but the difference was not significant. However, for the gain in investigation skills, there was a significant difference, in favour of the inquiry group. The researchers conceded that several factors could have influenced the results, noting particularly that in their school years prior to university the students would have encountered mainly the prevailing cookbook laboratory work, as shown in the 2015 PISA results for the Czech Republic (Blazeb and Prihodova, 2016). The novelty of inquiry-based work could have been either confusing or inspiring to students in their university course.

4.1.8 12-year longitudinal study of science concept learning

Novak (2005) studied the impact of early exposure to science concepts on students subsequent learning in science. In 1971, when the study began, there was little science taught in primary schools, partly on account of the influence of Piaget's developmental psychology, on the basis of which many argued that children would not understand science concepts until the stage of formal operations, at around age 14 – 15. In the study, children in grades 1 and 2 (aged 6-8) in a 'treatment group' listened to recorded lessons about science concepts and were then followed up over the next 12 years by interview and their performance compared with a control group. The treatment was focused on science content knowledge, with no reference to procedural or epistemological knowledge. Clear differences were found in favour of the treatment group throughout the following 12 years and further into high school years. The conclusion drawn was that there was no case for delaying instruction in science until students reached Piaget's formal operations stage. It also showed that early experiences can have long-term effect and led to the recognition that science should be part of the curriculum throughout the years of school.

4.1.9 Effect of students' emotional intelligence on their response to IBSE

This study, carried out in Indonesia (Nasution, 2018), compared the science achievement of two classes of grade 7 students, one being the experimental group taught science using an inquiry-based approach, and the other acting as a control taught science by conventional methods. Students in both groups were identified as having lower or higher emotional intelligence (EI) based on their learning motivation, social skills, self-regulation, empathy, and high-level thinking skills. Using a pre- and post- test design, change in science scores was compared for students in the two groups and for those with high and low EI. It was found that students in the IBSE group improved their science scores to a greater extent than the control students. However, the students with higher EI in the experimental group the difference was much greater. Moreover, students with lower EI achieved more in the control group than they did through IBSE. The author suggests that those students with high EI possess many of the characteristics that favour learning through inquiry, whilst those with lower EI take less responsibility for their learning, prefer to follow instructions and work alone rather than in groups. These characteristics should be taken into account in deciding how best to help students' science learning.

4.2 Main findings from research on student response and achievement

About impact on student response and achievement

- The longer students are involved in using an inquiry-based programme the more they benefit from it in comparison with those not involved.
- Students with experience of using inquiry-based activities perform well in tests of critical thinking and problem solving.
- The more students have direct, hands-on experience of objects and events in the world around the better their conceptual learning.
- All students find inquiry-based activities interesting and useful and learn from them, although they show no significant change in attitude to science.

- The few reports of gender differences in achievement are small and not statistically significant.
- Gender differences in engagement in science activities and in career expectations appear to be more related to what boys and girls think they are able to do, rather than what they actually can do.

About teacher education and support

- Teachers need to take account of characteristics of students, such as a predisposition to take responsibility for their learning and other aspects of emotional intelligence, in helping students undertake inquiry-based activities.
- Teachers need science-specific pedagogical skills and procedural knowledge, not only science content knowledge, for implementing IBSE programmes. A high level of teacher content knowledge does not compensate for lack of pedagogical knowledge.
- Students whose teachers have pedagogical training benefit from inquiry-based activities to a greater extent than others whose teachers do not have a formal teaching qualification.
- Provision of a coordinated range of different forms of support for IBSE, including teaching material, professional development and use of assessment, can improve student achievement in other areas as well as science.

About research procedures

- Caution is needed in interpreting correlations derived from cross-sectional survey data, such as PISA.
- The inquiry experiences provided in an IBSE programme should be made clear by specifying the actions and roles of students and teachers.
- The evaluation of new inquiry-based programmes or approaches is best delayed until they are well established in practice.
- Teachers may claim to be using an inquiry-based programme but, due to various constraints or insufficient training, spend less time on IBSE lessons than is necessary to properly implement the approach.
- Systematic synthesis of the outcomes of several research studies on a topic can produce more reliable findings than individual studies alone.

4.3 Other research and arguments

As these points from research show, the evidence of impact on student achievement to date does not amount to overwhelming endorsement of IBSE (Yeomans, nd). But there are other fields of research that are increasing our understanding of learning and provide arguments in favour of inquiry-based education.

The first concerns views of how learning takes place. Developing understanding through inquiry, as represented in Figure 1, accords with a view of learning as a process in which learners make sense of new experience by using their existing ideas; that is, a constructivist view of learning. But current understanding of learning goes further in recognising that learning is not just an individual matter but involves social interaction (Watkins, 2003). Through interaction with others in a collaborative group, each person takes something from the group discussion which then influences their contribution to the group. Through this to-ing and fro-ing from individual to group, understanding is constructed together, in a manner described as socio-cultural constructivist, with language and physical resources taking important roles. Hence the emphasis on talk and dialogue in learning (e.g. Alexander, 2012), but also on ways in which people interact with others through reading what they have written or looking at what they have produced and, equally, sharing their own ideas through writing as well as talking.

Inquiry-based learning, in which knowledge is constructed through the active participation of learners is often contrasted with direct instruction, where learners are passive receivers of knowledge. Learning science involves not one or the other but both, at different times. When there is a need to learn names, procedures and techniques, that are required for first-hand investigation, there is a role for direct instruction, as there is in learning about the early ideas and work of scientists in the past. But building knowledge progressively, bringing together new experience and existing ideas, requires actions that have been identified as integral to IBSE (see Section 2).

A second source of relevant evidence and argument relating to inquiry-based learning is the rapidly expanding knowledge of the structure and function of the brain and of links between neuroscience and education. It makes sense that there should be some relationship between what happens inside the brain and response to events outside; indeed, studies show that learning changes the brain both in structure and size. The relationship between the internal structure of the brain (see Box 4) and the aspects of external environment that are under the influence of education, is of particular interest for improving the effectiveness of teaching and learning. As well as providing new knowledge about learning, neuroscience has explained the impact of external conditions already recognised in everyday experience: for instance, the benefits for young learners of good diet, regular physical exercise and sleep; and, for older people, how mental activity, social interaction and regular exercise can delay brain degeneration (OECD 2007).

Box 4 The structure of the brain

The brain is composed of neurons, cells which have two main parts: the cell body, which contains a nucleus with DNA, and elongated projections such as dendrites and axon. Dendrites are thread-like, branching structures which grow out of the cell body, whilst the axon is in most cases a single fibre, much longer than the cell body. The activity of the brain depends on communication between neurons. The communication is through electric signals which are the result of movement of ions (atoms and molecules that have a positive or negative charge), within and surrounding the neuron. Without going into detail of how charges move into and out of a neuron, these electric signals are transmitted by one neuron to another by axons and received from another neuron by dendrites. This cell-to-cell communication occurs at specialised sites called synapses, namely small gaps between the terminal of an axon of the cell sending a message and the dendrite of a receiving neuron. If several signals are received in a cell body their combined effect can 'excite' the cell body and send a signal across the gap to another neuron. Each neuron can communicate with many others, forming networks. It is these networks of communications that enable the brain to carry out its functions.

Memory has a central role in how a person responds to experience. In the context of learning through inquiry it means that past experience can be brought to bear in trying to make sense of new experience or solve a problem, as in the sequence of events depicted in Figure 1. Studies show that there are several stages between receiving information through the senses and having it established in long-term memory, where it becomes available for use in making sense of new experience. These stages involve sensory memory, short-term or working memory, and long-term memory. Sensory memory lasts for a very short time and information will only be transferred to working memory if a person pays attention to it. Transfer to long-term memory (of which there are various kinds) has been the subject of many studies. Findings relevant to learning include that writing down or making some representation of a problem improves ability to solve problems. Apart from other advantages, external representations can help offload some of these heavy demands upon working memory (Howard-Jones et al, 2007:17).

In addition, it has been found that there are separate channels for processing information in visual and verbal forms, and since there is a limit to the information that can be processed through any one channel at a time, the use of different channels, as in multimedia approaches to teaching, can increase the total amount of information a learner can take in. But when there are many things to attend to, as in tasks requiring making decisions about all parts of conducting inquiry, this may require too much working memory, leading to what is described as cognitive overload (see 4.1.2). This theory is used to explain why moderate levels of inquiry are more strongly associated with increased achievement, than very high levels (Jerrim et al, 2019).

Studies have also shown that emotional response to experiences is related to cognitive response and can affect learning. The close relationship of feeling and thinking shows in the pleasure a person feels from solving a difficult problem – and in the frustration felt when not able to understand something. The pleasure is not only a reward for completing a task successfully but is a motivation for tackling further tasks. Negative emotional response, on the other hand, can interrupt learning (see 4.1.9). So, teachers and students need to be aware of these feelings and find ways of making learning rewarding, ensuring that students recognise the progress they have made and that they have learned something even when things ‘didn’t work’.

A key feature of socio-constructivist and inquiry-based learning is collaborative work, in which students share ideas, learning from and with others. Studies of the brain show that it has features that are adapted to this way of learning. So-called ‘mirror neurons’ prime a person to mimic in their own behaviour what they see others doing. This disposition to imitate or copy behaviour is one of the main ways in which cultural habits of thinking and learning are transmitted from one generation to the next (Hurley and Chater, 2005). Through interaction with teachers, parents and other adults, children are socialised into society and internalise beliefs and values (Hinton and Fischer, 2010). By watching others, they also learn to moderate their emotional response to experience.

5. Obstacles to implementing IBSE

Teaching and learning science, either through IBSE or other ways of teaching, requires: financial, physical and material provision, including learning and teaching resources appropriate to the age and stage of students; equipment; physical space; access to sources of information, books; and computers. Lack of these is likely to restrict science activities of any kind, but in the case of IBSE there are additional factors that challenge implementation in both primary (IAP, 2009) and secondary (IAP, 2010) education. Such potential obstacles to implementing IBSE are the focus of discussion in this section. It is followed, in Section 6, by suggestions emerging from research and practice as to how the challenges they present might be met.

5.1 The concept of IBSE

The use of a variety of terms (such as in Box 1 p3) to describe what is intended to be essentially the same process can send mixed messages to those trying to implement IBSE or communicate its importance. The position is further confused when additional concepts, such as 'inquiry saturation' (Minner et al, 2010), 'pure' inquiry (Jerrim et al, 2019) and reference to 'levels' of inquiry, are introduced in describing research findings without being defined.

Uncertainty arises especially in relation to the role of teachers in supporting learning through inquiry, which is far more than the provision of materials and learning resources, and is often described rather vaguely as 'facilitator' rather than specifying the actions and roles involved. This can lead to teachers missing opportunities to help students take next steps in developing their understanding and failure to recognise the role of IBSE in developing students' conceptual knowledge.

In addition, taking too narrow a view of the range of topics for inquiry-based activities can result in over-emphasis on inquiries involving physical action in manipulating objects and materials and neglect of inquiries relating to phenomena where evidence is gathered from secondary sources, surveys or careful observation, rather than experiment.

5.2 Teacher education

What teachers do when helping students to learn through IBSE has been made explicit in Section 2.4. Those actions require not only knowledge of the subject matter but knowledge of how to bring students to engage productively with the subject matter and how to help them develop their understanding. The concept of 'teacher-proof' curriculum material (briefly entertained in the 1960s) has ceased to have any validity, and the teacher's role in students' learning is now seen as paramount (Hattie, 2003; Hodson, 1998). When teachers do not have the training necessary to develop the knowledge and pedagogic skills to guide inquiry, students are unlikely to have the opportunity to benefit from learning through IBSE.

Often teachers of science, particularly primary school teachers (who may not regard themselves as 'science teachers') worry about the extent of their personal knowledge of the science content and, in response, teacher educators focus their pre-service and in-service courses on filling gaps in teachers' content knowledge. But research (e.g. Mellander and Svärdh, 2018) shows that increasing teachers' subject knowledge alone is not associated with improvement in student learning: instead, improved learning is associated with teachers having more of the skills needed to encourage students in using inquiry skills. Moreover, providing this pedagogical training is found to be associated with improved achievement in other areas of study, such as mathematics and reading (Zoblotsky et al, 2017).

5.3 Assessment

"Assessment is one of the most important driving forces in education and a defining aspect of any educational system" (Rönneback et al, 2018: 28). It is one of three interconnected components of students' learning experience, the others being curriculum content and pedagogy. The interconnections among these three means that changes in any one of them will have consequences for the others. In particular, it implies that what is given priority in assessment will tend to be given priority in what is taught and what pedagogy will be used in teaching (Harlen and Deakin Crick, 2003). All assessment will, to some extent, influence what is taught and how it is taught (IAP, 2010:16) so it is important to consider how the assessment process and the use of assessment can affect the practice of inquiry-based teaching and learning.

Assessment in education is generally taken to be a process in which evidence of students' achievements is gathered, interpreted, and used for some purpose(s), the main purposes being: formative, to help further learning; and summative, to report what students know and can do at a particular time.

Formative assessment is, by definition, assessment that helps learning. It does this through the processes of "seeking and interpreting evidence for use by learners and their teachers to decide where the learners are in their learning and where they need to go and how best to get there" (ARG, 2002). In other words, it starts from what learners already know and can do in relation to the goals of their current activities and uses this to inform decisions on how to make progress.

This is also what teachers do when implementing IBSE – using information about progress to create the conditions for students to construct their understanding and develop skills of scientific investigation. It follows that formative assessment, as defined, has much in common with, and integral to, inquiry-based pedagogy. The widely reported neglect of the formative assessment, due to over-emphasis on summative assessment, inhibits the implementation of inquiry pedagogy.

The position in relation to summative assessment is quite different. Summative assessment has a well-established role in providing information on students' achievement. It is part of teachers' role to report to parents on their children's progress at key points, to keep track of students' achievement as they pass through school and to inform students' later teachers. For these and other reasons, summative assessment is necessary, is often a statutory requirement, and cannot be avoided. By contrast, formative assessment could be considered voluntary, in that it is possible to teach without it, and teachers have some choice about whether to do so. It follows that teachers need to be convinced of the value of formative assessment and its use in IBSE.

Unlike formative assessment, it is not the main rationale of summative assessment to impact on learning and teaching. However, the way in which the results of summative are used can have consequences for individual students, as when used for selection or certification, and for their teachers and schools, when used for accountability purposes (see 5.4). How the evidence about achievement is collected and, more importantly, what evidence is collected, is taken as indicating what learning is worthwhile. Indeed, Osborne and Dillon (2008) note that teachers increasingly look "not to the curriculum specifications to define what the intentions of the curriculum should be but to the assessment items" (p 23).

All too often there is a gap between what ought to be assessed for a valid summary of learning and what is assessed. The gap is likely to be particularly large in the case of IBSE, given the nature of the intended learning outcomes, which are not easily assessed by conventional methods. Basing teaching on what can be assessed when this does not reflect the learning outcomes of IBSE is clearly particularly problematic. Consequently, unless summative assessment methods and instruments are compatible with the learning outcomes of IBSE, it can inhibit the implementation of IBSE.

5.4 Accountability

Summative assessment results may be used in different ways, some relating to individual students and some to the use of aggregated results of groups of students. Aggregated results for groups are used both by those within and outside the school. For instance, school principals may track the progress of groups according to gender, ethnicity or other aspects of their background to check for possible bias in provision of opportunities for all, while the performance of groups may be used by inspectors and advisers in the evaluation of school programmes, policies and resources.

More controversially, aggregated assessment results, usually derived from conventional tests of basic knowledge, may be used by agencies and authorities to set targets and evaluate the performance of teachers and schools. This use of summative assessment results to judge the effectiveness of teachers and schools is regarded by many as unfair, particularly when there are penalties for not reaching targets. Moreover, research (eg Hall and Øzerk, 2010; Wyse et al, 2010; Linn, 2000) provides convincing evidence from classroom observations of the impact of what is tested on teachers and teaching: spending excessive time on revising and practising what is tested; narrowing the curriculum to what is assessed; adopting a transmission pedagogy even though this was not what they believed to be the best for helping students' understanding and development of skills.

Teachers and schools are responsible for the learning experiences and environment that they provide and the help they give to students. Other factors influencing students' achievement, such as their prior learning, family background and support (see science capital, Section 3.6), over which a teacher may not have control, need to be taken into account by those who hold teachers accountable for the quality of students' learning.

Relevant to the issue of what schools are accountable for is their power to decide matters of provision and use of resources. Information about the degree of autonomy the school has in these matters, collected from school principals in the 2015 PISA survey, was used to investigate relationships between the degree of autonomy, school variables and science performance. The findings showed a complex pattern of association between science scores, school autonomy and school socio-economic status. In more economically advantaged countries schools had greater autonomy than in less advantaged countries. On average, across many countries, having more responsibility was associated with higher science scores, but after allowing for socio-economic status, there was little association with science performance. Looking at different areas of responsibility, higher science scores were found to be positively associated with the school principal or teachers having greater responsibility across all areas but especially for curriculum and assessment policies. This suggests that implementation of IBSE may be held back when such decisions are taken by authorities outside the school.

5.5 An overloaded curriculum

Putting inquiry into practice effectively is frequently considered to be more time-consuming than direct instruction, although it is not possible to compare these approaches fairly as their intended and unintended outcomes are so different. The pressure that IBSE is seen to put on precious learning time, in the face of an overcrowded curriculum for science, is a common reason given for not spending the time required by inquiry-based programmes, as noted, for instance, by Alberg (2015) in Section 4.1.4.

Many causes of overcrowding of science curricula originate in factors beyond IBSE, however, such as attempts to keep abreast of the rapidly expanding knowledge revealed by scientific research, the need to prepare students to meet changes in the world of work, and to meet the challenges related to global issues of climate change, population, etc. But part of the problem lies in the over-specification of the curriculum as a series of disconnected facts to be learned and assessed (Millar and Osborne, 2000). Such curriculum specification often leads to teachers rushing from one topic to another and discourages spending time on linking ideas together to form more powerful and widely applicable concepts.

5.6 Expectations of teaching and teachers

Long standing traditions and assumptions about education can act as brakes on change in many areas, but particularly in education, where expectations about the roles of teachers and students are passed from one generation to another in patterns of training and certification. The views of parents and other stakeholders in education on what teachers should be teaching and students should be learning also have a restraining effect on the extent of, and rate at which, changes can be made.

Studies of the implementation of IBSE frequently cite the established and traditional teaching methods as reasons for what is implemented in the name of IBSE often falling short of what is required (e.g. Kekule et al, 2017; Mellander and Svärdh, 2018). When students have been used to a passive role of receiving information and achieving success through memorising, they are likely to feel insecure when expected to be more active and to think for themselves. Teachers respond to this by closing down opportunities for students to raise questions and reverting to more familiar teacher-led methods (Harlen and Holroyd, 1997).

5.7 Resources for teaching science

Learning resources include all the factors that have a part in students' learning in science, including books, computers, materials and equipment, time, suitable space, well-trained teachers, peers and, of course, money. The emphasis in IBSE on active learning, collection of evidence, group work, discussion and dialogue makes greater demands on these resources than teacher-directed or 'cook book' exercises. In secondary schools the extent of provision of laboratories and laboratory staff can be limiting factors, while in primary schools the main difficulties are large classes, inadequate space and resources and lack of teaching assistants.

In relation to expenditure on education, data collected in PISA 2015 confirmed the findings of previous research that "once an adequate level of resources is reached, additional resources may not necessarily contribute to better learning outcomes" (OECD, 2016:186). The results showed a positive association between overall spending per student and science performance in countries where spending per student was at or below a certain level (about 50,000 USD in2015) but at greater levels of expenditure (mainly Western, developed, countries) there was no longer any relationship. It appears, then, that overall expenditure may have a limiting effect on science performance only in lower capital GPD countries and economies. In the higher GPD countries it is not the overall level but other factors that influence performance.

Data gathered in PISA 2015 shed some light on what these other factors may be. Information about the adequacy of laboratory equipment and staff, and the education of science teachers, was put together to create an 'index of science-specific resources'. This index was then used to explore relationships between factors relating to science teaching with school characteristics and science outcomes. Across all PISA participant countries and economies there were consistent differences related to schools' socio-economic status. Differences between advantaged and disadvantaged schools were particularly high in some countries e.g. Indonesia and Mexico. Other differences were noted between urban and rural schools, in favour of the former, and between private and public school, with private schools being reported as better equipped.

In OECD countries, the science-specific resources index was positively related to better performance in science, after accounting for the socio-economic profile of the school. But only in a few countries was there a positive association between the index and the students' understanding the nature of science (epistemic knowledge), suggesting that a well-equipped and well-staffed science department did not necessarily translate into the quality and aims of science lessons.

Data collected from school principals about the training and qualifications of their science staff showed that science staff generally had some form of certification. However, in most systems there was no association between the proportion of fully qualified science teachers and student performance. This endorses a finding from other empirical studies (e.g. Goldhaber and Brewer, 2000) that teacher certification does not automatically raise student achievement.

6. Implications for policy and practice

Section 5 discussed potential obstacles to the implementation of IBSE which were identified in research studies and examples of practice, discussed in previous sections. Some of these sources also point to possible solutions. This section brings together proposals for addressing the problems created by these obstacles.

6.1 Implications for the concept of IBSE

The discussion in Section 2 of the meaning of IBSE points to the need for clarity about using terms such as ‘guided inquiry’ and referring to different ‘levels’ of inquiry or ‘inquiry saturation’. Lack of more precise descriptions could well account for the frequent finding of ‘no significant difference’ in research studies of IBSE impact.

Instead of categorising a programme or activity as ‘IBSE’ or ‘non-IBSE’ or as some form of ‘guided’ inquiry, a more informative approach would be to describe its features that contribute to students’ development of the knowledge and skills of scientific literacy. A possible approach would be to distinguish between the quality and quantity of the actions of students and teachers: quality expressed in terms of the actions of students and teachers in sections 2.2 and 2.4; quantity being the frequency and duration of these actions.

Where students undertake some, but not all, actions involved in inquiry their experience could be described in terms of ‘levels’ of inquiry, with the nature of the actions undertaken being specified. The frequency of experience of inquiry-related activity could be used to describe the experiences as ‘high’, ‘medium’ or ‘low’ intensity. Providing more detailed information of what a certain IBSE programme means for student and teacher activity would facilitate more valid evaluation of the effects of IBSE. Without specification such as this, it is uncertain as to what is actually producing an impact on students.

6.2 Implications for teacher education

Initial teacher training and professional development should enable teachers to understand the role of inquiry-based activity as an important part of a range of pedagogical skills needed in teaching science. Teachers will need the specific pedagogic skills that help students develop their inquiry skills and their understanding of the world around, taking advantage of the opportunities that the use of ICT offers to enrich learning experiences (see 3.3). They also need to be able to judge the level of guidance required that ensures students receive help needed to make progress but still think for themselves. Key pedagogic skills are focused questioning and scaffolding alternative ideas for students to consider as well as their own ideas.

As noted in Section 2.4, the form, content and timing of teachers’ questions have an important part in framing students’ activities and guiding their learning. Evidence from classroom observation shows that teachers’ questions are often of low cognitive demand and funnel students’ response towards a required answer. Implementing inquiry requires a range of different types of questions appropriate to the stages of the inquiry process; all challenging students to think. Teachers also need to recognise also that thought-provoking questions require time for thought and they should resist the urge to fill any silence by rephrasing a question in a way that closes down the thinking (Harlen and Qualter, 2018: 141-3).

Extending students’ exploration of the world around is an acknowledged purpose of all science education; but if students are to make sense of new experiences, they also need to expand the range of ideas they use. Helping students to consider ideas different from their own is a key aspect of inquiry pedagogy. Scaffolding (see also Section 2.4) is a strategy that allows students to consider ideas that they had not thought of to see if they ‘work’; it is especially useful when ideas cannot be tested by practical manipulation such as ideas about the causes of day and night and phases of the Moon.

6.3 Implications for assessment policy

Given that summative assessment is necessary and has several positive functions in education, there is an urgent need to counter its potential negative impacts, such as noted in Section 5.4. It is unlikely that the influence of what is assessed on what is taught can be prevented, but it could be used to advantage, to promote the teaching of desired goals, such as creativity, problem-solving, learning how to learn, by including them in assessment requirements. Since absence of IBSE goals in many current assessment systems is a factor holding back implementation, then one answer is to include more of the IBSE goals in what is assessed. Although there are examples in current practice to show that this is possible (IAP, 2013; Harlen, 2007), it is likely that it will involve moving away from traditional assessment methods based on tests and towards making more use of teachers' judgements and new technologies.

6.4 Implications for accountability policy

Being held accountable means being responsible for actions taken and being able to explain why and how certain things were done or not done. It follows that

> "the information used in accountability should include, in addition to data on students' achievements, information about the curriculum and teaching methods and relevant aspects of students; backgrounds and their learning histories" (IAP 2013: 30).

An approach that could be more effective in improving the performance of schools is described by Smith (2016) as 'internal' accountability, involving:

> "greater autonomy for schools, where they set their own goals and use an audit system to evaluate to what extent these have been met. Internal accountability is accompanied by a high level of responsibility" (p 749).

This process has been facilitated by the development in New Zealand (Crooks, 2003), by agencies in the UK (HMIe, 2007) and by the Fibonacci Project (EU, 2012) of self-evaluation frameworks for schools to use in reviewing their practice against criteria of effectiveness and in setting targets for improvement. School self-evaluation reports enable schools to explain to stakeholders how they are working towards targets within the constraints that affect their students' performance. This avoids schools being judged solely on their students' assessed performance, incurring all the problems of validity associated with assessment methods.

6.5 Implications for curriculum structure

Curriculum overload and a scramble to 'cover' the curriculum are frequently cited reasons for failure to use inquiry-based activities. A possible solution to this problem is proposed in the publications supported by the IAP on Big Ideas of Science Education (Harlen, 2010 and 2015). This would conceive the aims of science education not in terms of a body of facts and theories, but as a progression towards a limited number of key ideas – described as 'big ideas' because they help to explain a number of related events and phenomena (see Box 5).

Learning science is then seen as gradually developing a grasp of a relatively small number of widely applicable ideas that help to explain aspects of the world around. As well as being concerned with content, there are big ideas that relate to the nature of science and to procedures of scientific investigation. Learning through inquiry, as depicted in Figure 1, has a key role in enabling students to link existing ideas with new experiences to create bigger ideas. Identifying learning goals in terms of a few big ideas, rather than a multitude of facts and theories, creates space in the science curriculum for learning through inquiry.

Box 5 Big Ideas of science education (from IAP, 2015)

Ideas of science

All matter in the Universe is made of very small particles.

Objects can affect other objects at a distance.

Changing the movement of an object requires a net force to be acting on it.

The total amount of energy in the Universe is always the same but can be transferred from one energy form to another during an event

The composition of the Earth and its atmosphere and the processes occurring within them shape the Earth's surface and its climate.

Our solar system is a very small part of one of billions of galaxies in the Universe.

Organisms are organised on a cellular basis and have a finite life span.

Organisms require a supply of energy and materials for which they often depend on or compete with other organisms.

Genetic information is passed down from one generation of organisms to another.

The diversity of organisms, living and extinct, is the result of evolution.

Ideas about science

Science is about finding the cause or causes of phenomena in the natural world

Scientific explanations, theories and models are those that best fit the facts known at a particular time.

The knowledge produced by science is used in engineering and technologies to create products to serve human ends.

Applications of science often have ethical, social, economic and political implications.

6.6 Implications for making changes

Section 5 showed that making change needed to implement inquiry-based teaching encounters obstacles of different kinds. Faced with resistance from many directions, an effective response necessarily requires action on several fronts. Studies show that providing new classroom resources is not sufficient. Teachers should have opportunity through professional development to understand the rationale for, and become committed to, new practices (Black et al, 2003). These are likely to include change in relationships between teachers and students and in the dynamics of the classroom, requiring the establishment of new social norms – a form of 'didactic contract' between teacher and students. All of this takes time and a coordinated range of inputs, similar to those provided in the LASER model of curriculum change (Alberg, 2015), designed to ensure that teachers have professional development, classroom resources and help with assessment, and that schools have community support.

6.7 Implications for resources

Section 5.7 noted the complex relationship between countries' science scores, expenditure on education and the level of per capita GDP, found in the PISA 2015 survey. Among countries with a low GPD per student, greater expenditure on education is in general associated with higher levels of student achievement. Reasons for the difference are likely to be related to aspects of provision identified in the 'index of science-specific resources', such as adequacy of laboratory equipment and staff, the education of science teaching staff, and the availability of materials for hands-on activities. Although the relationship is not cause and effect (adding resources will not necessarily lead to improved science achievement), it does offer the possibility of action to improve opportunities for learning in economically poorer countries. However, in the case of richer countries, with a GDP above a certain level, greater expenditure is not associated with higher levels of student achievement. For these countries there appears to be no advantage in terms of higher levels of performance of merely adding more resources. Instead, there is evidence that average performance may be raised by considering how resources are allocated and used within schools.

In both rich and poor countries, there is room for raising levels of science performance by reducing the gap in resource allocation between school attended by advantaged and disadvantaged students. PISA reports show that in countries where more resources are allocated to disadvantaged schools than to advantaged schools, overall student performance in science is somewhat higher. Furthermore, it is suggested that "low-performing students appear to benefit the most when more resources are allocated to disadvantaged rather than advantaged school" (OECD 2016a:189).

In brief, then, it seems that to help all countries raise levels of student performance the allocation of resources between advantaged and disadvantaged schools should be reviewed and, if necessary, adjusted. But increased expenditure and quality of resources does not necessarily translate into improvement in student achievement. For that, the PISA 2015 findings point to the time spent in learning science and the methods used in teaching as having a much greater impact than the material and human resources devoted to learning science (OECD 2016:3).

7. Recommendations

This report began by discussing the meaning of IBSE and its important contribution to the development of the content knowledge, skills and understanding of the nature of science that constitute scientific literacy. A review of research studies on the effects of using IBSE, whilst not providing resounding support, indicates its potential to improve students' learning. At the same time, it reveals several factors that have obstructed its implementation and implications for action to avoid them. These are the basis of the following recommendations for policy.

In relation to the aims of science education

R1 The aims of science education should be seen as the development of scientific literacy and of the knowledge of content, procedures of scientific inquiry and the nature of science which it comprises. Inquiry-based pedagogy should be recognised as having a key role in the development of a scientifically literate population.

R2 The values of IBSE in developing knowledge and skills that are of benefit to everyone as individuals and as members of society should be widely publicised and shared with policy makers.

R3 Steps should be taken to increase awareness of the wide range of careers and occupations that involve scientific knowledge and skills, and to persuade more females and those in other under-represented groups to aspire to careers in science, increasing participation in STEM subjects.

In relation to the professional development of teachers

R4 Pre-service teacher education and professional development for teachers should include development of pedagogical skills used in inquiry-based teaching, not only science content knowledge. The duration and structure of courses should allow for the gradual development of teachers' understanding of the processes of learning underlying inquiry pedagogy and commitment to using it.

In relation to formative and summative assessment of student achievement

R5 Attention should be given to using assessment formatively by finding what students already know and can do and using this information to advance their learning.

R6 The content and procedures of summative assessment in science should reflect the key learning outcomes of IBSE including content, procedural and epistemic knowledge. The frequent use of summative tests which take up valuable learning time, should be avoided and replaced by moderated on-going assessment by teachers.

In relation to accountability

R7 Information used in evaluating teachers and schools, and in school self-evaluation, should reflect the aims of inquiry-based learning. The achievement of groups of students should be set in the context of students' economic background and the degree of the school's autonomy over the curriculum, resources and teaching methods.

In relation to curriculum structure

R8 The content and form of national curriculum specifications should be reviewed to avoid curriculum overload. The curriculum content should be expressed as a limited number of key scientific concepts ('big ideas') that are progressively developed through primary and secondary education and beyond.

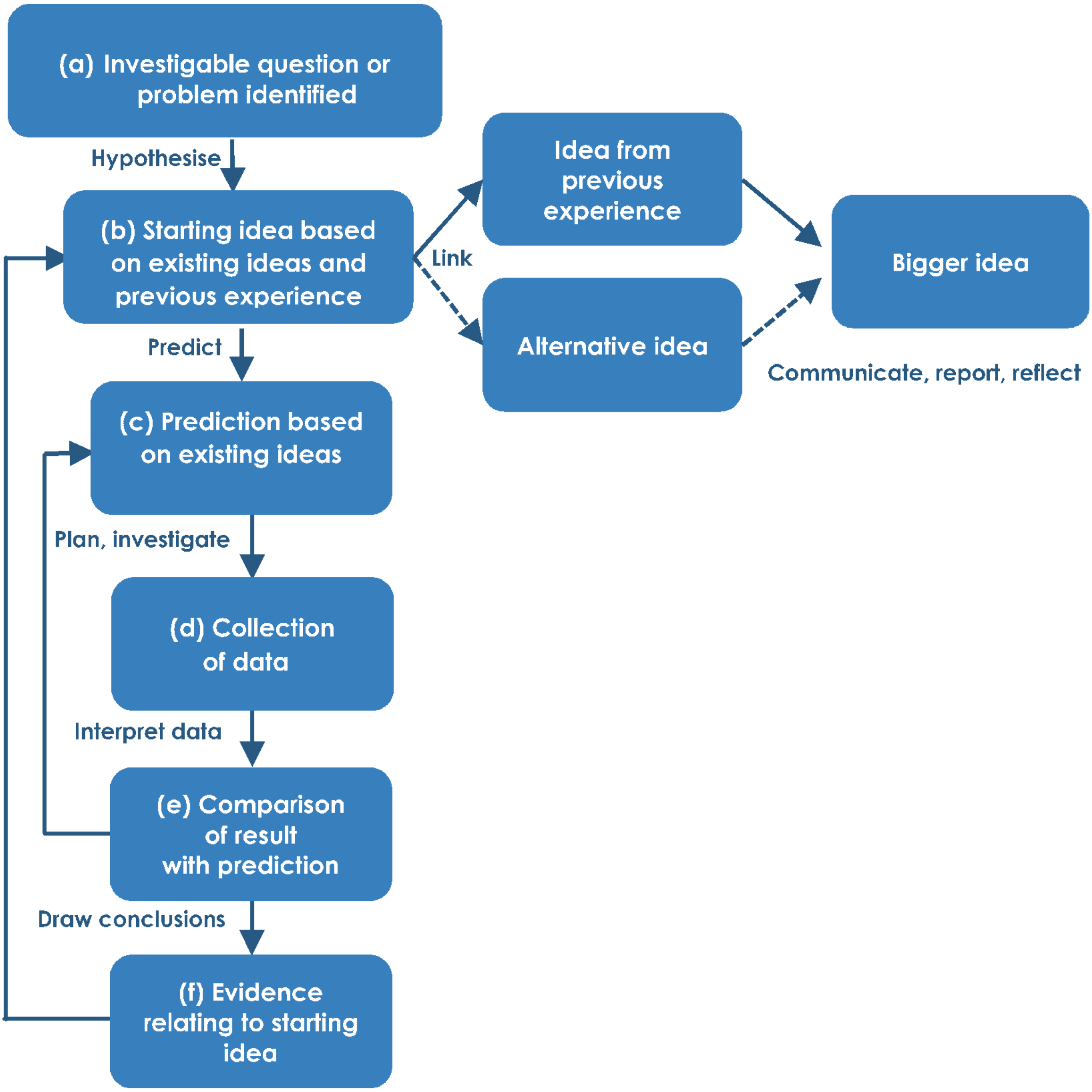
In relation to resources

R9 It should be recognised that increasing the quality of and level of expenditure on science-related teaching resources can improve student attainment in countries with low per capita GDP, but in other countries time spent learning science and the teaching methods used have greater impact than material resources.

In relation to research

R10 There should be more efforts to provide valid and reliable research evidence about the long-term effects of IBSE, with particular attention to gender differences. To guide the development and implementation of IBSE, systematic reviews of research should be commissioned to provide more reliable information than individual studies.

Figure 1 A model of learning through inquiry in science



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