PISA: Engagement, Attainment and interest in Science (PEAS)

Final report

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Advisory Board

Our thanks extend to members of the Advisory Board who gave their time throughout the project and colleagues Andrew McConney, Amanda Woods-McConney and Sam Sims.

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Executive summary

The way in which science is taught can influence how interested, engaged and informed students are. Teachers are responsible for the delivery of curriculum content as well as shaping views towards, beliefs about and ‘trust’ in science. Different instructional approaches are used by science teachers as they work with their students. This report explores the association between the experiences of learning science and achievement in fifteen-year olds in England. Our analysis draws from two large data sets: the National Pupil Database (NPD) and the Programme for International Student Assessment (PISA) 2015 data. In PISA 2015, the student questionnaire explored different classroom teaching strategies including teacher-led instruction, adaptive teaching and inquiry-based teaching. Inquiry-based teaching is contested as an instructional strategy with compelling but often opposing arguments advanced by policy makers, educators and researchers.

Background

School science attainment, attitudes and engagement are shaped by student background, school experiences, and social structures and expectations. Despite the various small studies that explore these relationships, there is little understanding of how these influences combine. Improving our understanding of these processes is essential for underpinning policies and practices to improve science learning in schools. Although research undertaken by Education Endowment Foundation (EEF) and The Royal Society (2017) show widening gaps in achievement associated with social disadvantage, no attempt has yet been made to explore or compare the effect of a range of school, system and student-level factors on achievement, interest and engagement. The release of Programme for International Student Assessment (PISA) 2015 data, and the capability to link these to the National Pupil Database (NPD), present a unique opportunity to explore the critical pre-General Certificate of Secondary Education (GCSE) period. We have identified important student (scientific literacy, attitude and engagement) and school-level variables (for example, such as instructional strategy, social advantage) on the pattern of science learning trajectories for the 2016 GCSE cohort.

We have taken a comparative perspective in exploring the science performance of 15-year-old students in the UK with students from other developed countries with a degree of shared cultural history, and more widely with OECD and partner nations to improve the external validity of findings. Specifically, we address the effect of different instructional strategies in science classrooms and increase our understanding of the student/school/system level interactions, particularly with respect to science subject interest, engagement and achievement. Given the enthusiasm amongst some leading science educators for ‘inquiry-based’ approaches, we wanted to explore associations between student-reported experiences of different instructional approaches and student achievement.

Methodology

Using data from PISA 2015 data, our analysis begins by presenting achievement data on the PISA assessment of scientific literacy (the ‘PISA score’) for each of the Anglophone countries (Australia, Canada, Ireland, New Zealand, United Kingdom, and the United States of America). The mean country data reflects different positions in the Organisation for Economic Co-operation and Development (OECD) rankings, which vary slightly from one round to another.

To determine the achievement score, or measure of scientific literacy, students answer a range of competency-based questions to determine ‘students’ capacity to apply knowledge and skills in key subjects, and to analyse, reason and communicate effectively as they identify, interpret and solve problems in a variety of situations’ (OECD, 2016, p. 25). Some examples of these questions are available (https://www.oecd.org/pisa/38709385.pdf) as released items from PISA. Coming towards the end of compulsory education, PISA assesses the extent to which different countries and systems of education have prepared their young people to be scientifically literate and informed citizens.

Students also respond to a short questionnaire about ‘themselves, their homes, and their schools and learning’ (OECD 2018, p. 3). Several items from the background questionnaire (e.g., parents’ education, parents’ occupations, home possessions, number of books, and other educational resources available in the home) are combined to form a student-level index representing socioeconomic status. In PISA, this variable is named the index of economic, social, and cultural status (ESCS) and is standardised to a mean of zero and a standard deviation of one (OECD 2016a).

PISA 2015 explored students' experiences of classrooms, of their teaching and learning experiences (see Appendix A). Students were asked about the frequency of certain activities ('never or almost never', 'some lessons', 'many lessons' or 'every lesson or almost every lesson') during their science lessons. Country comparisons are presented in PISA documents (OECD, 2016a, 2016b) detailing initial analysis and trends in performance, attitudes and equity, for example. The two-stage sampling process (first by school, then by student) used by PISA allows for national reporting priorities to be met and reflect the breadth of the student population in each country, even though some groups may be over-sampled. We draw from the publicly available primary analysis of the PISA data to retrieve their descriptive statistics (OECD 2016a, 2016b) in the first instance. Throughout this project, we used different statistical and modelling packages to address specific research questions. For example, we used the IDB Analyzer to produce descriptive benchmark analyses, and multivariate regression analysis, and to account for students' socioeconomic status (ESCS), as we examined the direction and relative size of the effect on scientific literacy for each instructional approach, while controlling for the other two approaches.

Findings

PISA data are generated from 15-year olds in schools. The OECD recognises that not all young people are in schools, so any analysis of these data needs to be understood with this caveat in mind.

- In all six Anglophone countries, students who reported experiencing high frequencies of inquiry strategies in their classrooms consistently evidenced lower levels of scientific literacy. There is a strong and negative association between inquiry-based teaching and scientific literacy, amounting to between 40-80% of a school year's learning.

- Conversely, we found a strongly positive association between the frequency of teacher-directed and adaptive teaching strategies and students' scientific literacy.
- Doing practical work either *every lesson* or *very rarely* is negatively associated with students' scientific literacy.
- While enjoyment of science is a predictor for GCSE science, instrumental motivation or a 'pragmatic reason' seems to have a greater predictive and positive association with 'A' level choices.
- The role of self-efficacy as (the largest affective variable) predictor of achievement, is an important finding and reflective of the beliefs that students have about their own ability to learn, master and likely to determine effort and aspiration.
- There is a positive association between inquiry-based teaching and 'positive dispositions towards science' (Cairns & Areepattamannil, 2019), such as enjoyment and interest in science (McConney, Oliver, Woods-McConney, Schibeci & Maor, 2104).

These are important findings to share with teachers and science educators in developing proficiency in using inquiry-based teaching. PISA data analysis of student responses to questions about the *frequency* of classroom experiences provide no insight into the *quality* of students' pedagogical experiences, so our recommendations are crafted with this in mind. The analysis shows complex, often non-linear associations between aspects of inquiry and scientific literacy (Jerrim, Oliver & Sims, 2019; Teig, Scherer & Nilsen, 2018).

Recommendations

Based on these findings, we recommend:

- Some aspects of inquiry-based teaching warrant greater support in schools: the cognitive rather than procedural and behavioural, or the 'doing' of science.
- Consistent with the predictions of cognitive load theory (see Kirschner, Sweller & Clark, 2006) we find that *moderate* levels of *highly guided* inquiry-based

teaching have a stronger (D≈0.2) relationship with student attainment on high-stakes GCSE.

- When science teachers use inquiry-based teaching, it should be carefully guided, well-planned and scaffolded (as this leads to positive cognitive and affective outcomes (Aditomo & Klieme, 2020).
- Teachers and schools use appropriate interventions to support self-efficacy especially in low socioeconomic status students. Importantly for policy makers, and those concerned to improve the quality of science education, attention needs to be given to how self-efficacy can be nurtured, developed and sustained in students.
- Environmental responsibility needs to be embedded into the curriculum from the early years.

Science is currently a 'poor relation' in the curriculum in many primary schools (Ofsted, 2021). Further research needs to explore the relative decline in performances in TIMSS, and of primary students in biennial tests and the extent of science experiences in primary schools in England. This will require exploring teachers' and students' experiences using observational classroom data.

Limitations

Although the survey organisers have reported the scale to have a high reliability, and our own robustness tests around this issue did not lead to a substantial change to our results, some attenuation of the estimated effects could nevertheless still be possible.

Rather than examining cause and effect, this is an observational study only, using student responses to the PISA ('low-stakes') assessment of scientific literacy and student questionnaire. Some science educators question the ability of students to 'judge teaching strategies'. Despite widespread support from science education and funding bodies (e.g. Association for Science Education, 2009; Holman, 2017), there is still a lively debate about whether the use of inquiry in science helps (Furtak, Seidel, Iverson & Briggs, 2012) or hinders (Alfieria, Brooks, Aldrich & Tenenbaum, 2011) pupil learning, including among policymakers (Gibb, 2017).

The focus of this study is on *frequency* of instructional approaches and not on the *quality* of classroom experiences. Although the measure of inquiry-based teaching within our dataset is based upon information reported by students, there may well be examples where inquiry-based teaching results in very high levels of student learning: we do not observe that using these PISA data. We cannot comment on the quality of the classroom experiences but the consistent patterning of responses across six (culturally similar) countries, suggests that the associations between achievement and instructional approaches are trustworthy.

We do not yet know whether the long-term and positive effects of inquiry-based teaching on students' dispositions to learning science may then encourage them to continue studying science beyond secondary school and on into a university degree.

Introduction

Science education is of primary importance for a scientifically literate populace and the workforce. Despite government policies to promote school science, teacher training bursaries and the evidence of the economic return to STEM, there are gaps both in participation and performance.

Over the last twenty years, international studies of educational achievement have grown in prominence and importance. Amongst these are a four-yearly assessment to determine the Trends in Mathematics and Science Study (TIMSS) conducted with students in Grade Four and Eight (Years Five and Nine in the UK) and a five-yearly measure of reading through the Progress in International Reading Literacy Study (PIRLS) of Grade Four students. The Organisation for Economic Co-Operation and Development (OECD) established a Programme for International Student Assessment (PISA) in 1997 providing a comparative measure of the performance of 15-year olds across OECD (and partner) countries in reading, mathematics and science literacies. More recently, financial literacy and problem-solving assessments have also been included. The triennial release of results from PISA now routinely receives considerable media, policy and political attention across the globe. At the same time, a wealth of academic studies is now conducted using these data, examining variation in young people and children's performance across countries, along with the factors that are associated with higher levels of achievement.

This secondary analysis of the PISA 2015 data has enabled us to better understand the relationship and association between achievement and instructional approaches, and between achievement and 'affect', providing new evidence on factors associated with student progress. UK PISA 2015 has been linked with National Pupil Database (NPD) and thus enables researchers to explore for the very first time the effect and possible interactivity of variables of students' achievement and progress in school science. We build on our previous work (Jerrim et al., 2015, 2016; McConney et al., 2014), The Royal Society (2017) and Sutton Trust (2015) reports in exploring relationships between socioeconomic status (SES), participation and achievement in school science using two large data sets in examining instructional approaches, achievement and affect in science in the population of the PISA 2015 and 2016 GCSE cohort. From this, we have identified a number of research questions:

1. *What are the levels of achievement, competencies and attitudes of fifteen-year olds in England and how do these compare with students in 'similar' countries in the different domains?*
2. *How are different teaching strategies associated with students' achievement in science? Specifically, how are the different aspects of 'inquiry' associated with their achievement?*
3. *Using the linked PISA 2015 and NPD, how do school and student-level variables determine (and predict) the pattern of science learning trajectories for the 2016 GCSE cohort?*
4. *How do students' attitudes towards and engagement with science as measured in PISA relate to GCSE and post-16 course completion?*
5. *How do students' levels of awareness of greenhouse gases vary across the OECD and partner countries? Is awareness of greenhouse gases associated with PISA score? How do student background variables and affective measures relate to students' levels of awareness of greenhouse gases?*

The Royal Society articulated a vision for STEM being 'essential to understanding the world and providing the foundations for economic prosperity' (2014, p.7), with an inspirational science curriculum, with an emphasis on practical work and problem-solving, a stable curriculum, and career-linked teacher professional development. The current UK government (2020) has articulated a vision placing science at the heart of the country's future prosperity. This project will help develop the understandings needed to deliver the ambitious aims of the Royal Society in exploring the relationships between and interaction of affect, attitudes and achievement.

Developments in science education

The purpose of science education has been articulated as two-fold, to 'educate students both about the major explanations of the material world that science offers and about the way science works' (Osborne & Dillon, 2008, p. 8). Criteria for determining a 'scientifically literate' young person have been articulated by PISA as,

> ...*the ability to engage with science-related issues, and with the ideas of science, as a reflective citizen. A scientifically literate person is willing to engage in reasoned discourse about science and technology, which requires the competencies to explain phenomena scientifically, evaluate and design scientific inquiry, and interpret data and evidence scientifically* (OECD, 2016b, p.28).

High levels of scientific literacy are linked to economic growth and countries showing greatest gains in PISA seem to have weathered the financial storm of the early part of the century well (OECD, 2010).

Year 11 in England is a particularly important time for pupils and their schools. At the end of this academic year, there are important national examinations, leading to the widely recognised General Certificate of Secondary Education (GCSE) qualification. The grades young people achieve have a significant impact upon whether they continue in full-time education beyond age 16, the type of higher education institution that they attend and, ultimately, their prospects when searching for a job. Moreover, as schools are publicly ranked and judged by their pupils' GCSE results, the academic progress young people make during this secondary school year is significant for teaching staff, too. Year 11 hence represents a crunch point in the English education system, where children are expected to work particularly hard, with significant pressure to achieve well.

In England, aspects of scientific inquiry have been a feature of the National Curriculum (NC) since 1989. The new NC includes a renewed focus on inquiry-based learning, as part of '*Working Scientifically'*. In line with this, the *Maintaining Curiosity* (Ofsted, 2013) report from the schools inspection body for England suggested that in order to develop understanding and achieve well pupils must 'enjoy the experience of working scientifically, and sustain their interest in learning it' (p.4); the best teachers 'put scientific inquiry at the heart of their teaching' (p.5); and they allow 'students to see the purpose of science learning and its inquiry-based skills within a wider context applicable to future careers' (p.34). More recent reviews from Ofsted distinguish between scientific inquiry, a process of developing scientific knowledge and a pedagogical approach Ofsted, 2021). Nationally and internationally, progress in developing or adopting inquiry-based approaches has been slow. PISA's conceptualisation of inquiry, to include procedural knowledge, the 'standard procedures that are the foundation of the diverse methods and practices used to establish scientific knowledge' (OECD, 2018, p. 73) as a key competency of scientific literacy. The *Good Practical Guide* (2017) highlighted the need for students to be involved in varied and regular learning practical experiences and reported that 'many schools are making too little use of their often-excellent practical facilities' (2017, p. 7). An international review of practical work pointed to the lack of evidence about the role of practical work in supporting student understanding, and whether this is primarily to develop skills, learn about science and scientists' work, conceptual understanding or dispositional and societal (Cukurova, Hanley & Lewis, 2017).

Inquiry-based teaching and learning

A global movement for improving science education in schools using more inquiry-based approaches has been evident for several years (see, Bell, Urhahne, Schanze, & Ploetzner, 2010; Furtak et al., 2012; Lazonder, & Harmsen, 2016; Minner, Levy, & Century, 2010) although some have urged caution in adopting inquiry-orientated teaching approaches for science teachers in schools (Hodson, 2014). The European Union (EU) funded a number of inquiry-based projects arguing that improvements in science education could be brought about with the introduction of inquiry-based approaches in schools, largely through ‘hands-on’ science (Rocard, 2007). The value and necessity of inquiry-based science education are presented by Harlen (2013), emphasising the need for inquiry-based science education where,

> ...*the value of IBSE is not a matter that can be decided by empirical evidence, but it is a value judgement that the competences, understanding, interest and attitudes that are its aims are worthwhile and indeed are necessary in a modern education (2013, p. 4).*

It is argued that inquiry-based teaching involves supporting students to acquire scientific knowledge indirectly by conducting their own scientific experiments, rather than receiving scientific knowledge directly from teachers. Key proponents claim that an inquiry-based teaching approach can help to: support and deepen learning of scientific concepts; overcome misconceptions as part of constructivist teaching and learning approaches; develop curiosity, engagement and interest in science; promote an understanding of the nature of science and what scientists do; develop future citizens who are able to make informed decisions about their lives. How to enact these ideals is not always clearly articulated. The 1996 National Science Education Standards from the US offers a more rigorous explanation,

> *Inquiry is central to science learning. When engaging in inquiry, students describe objects and events, ask questions, construct explanations, test those explanations against current scientific knowledge, and communicate their ideas to others. They identify their assumptions, use critical and logical thinking, and consider alternative explanations. In this way, students actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills*. (1996, p.1).

Precisely what is understood by ‘inquiry’ remains elusive and open to different interpretations. Is it about the nature of scientific practice, curriculum materials, or more concerned with teaching and learning (Rönnebeck, Bernholt, & Ropohl, 2016)? The variety of uses and meanings range from and include ‘an instructional approach, curriculum materials and a way for students to learn science’ (p.162). Science educators have promoted the benefits of inquiry-based learning (IBL) as the ‘method of choice’ for interest and achievement, as ‘current wisdom advocates that students best learn science through an inquiry -oriented teaching approach' (Lederman, Lederman & Antink, 2013, p.143). *Maintaining Curiosity* concluded that teachers perhaps lack confidence or 'understanding of the purpose of scientific inquiry and of the value of constructing activities that lead pupils to discover the scientific ideas' themselves' (Ofsted, 2013, p.10) making a case for 'more time for inquiry' (p.44), or investigative practical work. A renewed focus on the curriculum and support for pupils to access a high quality curriculum includes having appropriate practical resources to support teaching and learning (Ofsted, 2021). Practical work in science is of paramount importance in teaching and learning of science (Holman, 2017), that 'good quality practical work helps develop pupils' understanding of scientific processes and concepts' (Osborne & Dillon, 2008, p.3). However, as Osborne (2015) argued, the role and value of practical work has not always been articulated clearly, with the emphasis of 'doing' (procedural) rather than the 'thinking' or epistemic.

A developing trend is to focus more on the teaching and learning of science as 'argument and explanation' and less on 'exploration and experiment' (Kawalkar, & Vijapurkar, 2011, p. 2005) and evidence that students engaging in discussions helps assist their learning (Chi, 2009). In a meta-analysis of inquiry-based teaching Furtak et al., (2012) developed a framework to categorise the different aspects of inquiry, the types of instruction and student learning. They distinguished between the 'cognitive features of the activity and degree of guidance given to students' (p. 300) concluding that epistemic activities had the highest mean effect sizes compared with other forms of inquiry, namely, procedural, and social.

Apparent tension exists between advocates of 'more inquiry' and policy makers, and practitioners, responding to international comparisons. Closer to home, a recent Minister of State for School Standards responded to publication of the PISA data calling for changes in teaching strategies,

> *teacher-led approaches such as explaining how a science idea can be applied to a number of different phenomena had a net positive impact on pupil scores. Whereas allowing pupils to design their own experiments; allowing pupils to investigate and test their ideas; holding class debates about investigations; and requiring pupils to argue about science questions and a number of other 'child-*

centred' teaching approaches resulted in a net negative impact on science outcomes (Gibb, January 2017).

One view of inquiry-based teaching and learning in science reflects pedagogies in which 'students may be responsible for naming the scientific question under investigation, designing investigations to research their questions and interpreting findings from investigations' proposed by Nadelson, Williams, and Turner in their Campbell Collaboration systematic review (2011, p. 1). PISA's view of scientific literacy is aligned with understandings and expectations of three core competencies for students, 'explain phenomena scientifically', 'evaluate and design scientific inquiry' and 'interpret data and evidence scientifically' (OECD 2018, p. 72). We see PISA's conceptualisation and operationalisation of scientific literacy as including and embracing inquiry (OECD 2018; Sjøberg 2018). Important questions remain about what essential teaching and learning strategies comprise inquiry and to how these are related to the goal of scientific literacy for all.

Sources of data

This project has drawn from two large data sets, the NPD and PISA 2015 to explore relationships between variables associated with student achievement, engagement with, and interest in science. In particular, the linked NPD-PISA 2015 dataset presented an opportunity to address questions about the affective dimensions of participation and achievement in science at GCSE.

In conducting a comparative analysis, within Anglophone countries, we aim to demonstrate greater validity of the findings, being more generalizable. The Anglophone countries comprise the 'near neighbour' group for comparison. All share a common history, language, politics, economic development and culture. They also provide a stable group in terms of the distribution and patterning of data over the recent rounds of PISA, with Canada generally in the 'high-performing' group and Ireland and the US below the UK. All countries have been advocates of inquiry approaches in science teaching and learning with quite distinct patterns within some countries: the US with a more locally devolved system of school, for example.

Programme for International Student Assessment (PISA)

PISA data are routinely gathered from 15-year olds in schools, school leaders, teachers and parents of students in OECD (and partner) countries every three years. Each round of PISA has a particular focus on reading, mathematics or science. One of the OECD aims is to support the development of education systems preparing students with knowledge, skills and attributes for participating in developed economies. The student surveys are intended to be measures of these specific literacies rather than testing content knowledge of the school curricula and aim to capture,

> *students' capacity to apply knowledge and skills in key subjects, and to analyse, reason and communicate effectively as they identify, interpret and solve problems In a variety of situations* (OECD 2016a, b, p. 25).

Large-scale analyses of international data sets such as PIRLS, PISA and TIMSS have enabled researchers to explore and determine the association between different variables (such as the efficacy of different instructional approaches, student background, gender, epistemic beliefs, etc.) on student achievement and engagement (Cairns, 2019; Cairns & Areepattamannil, 2017, 2019; Jerrim, Oliver & Sims, 2019; Jiang & McComas, 2015; Lam & Lau, 2014; Lau & Lam, 2017; McConney et al., 2011, 2014; She et al., 2019; Teig et al., 2018; Woods-McConney et al., 2013, 2014).

This cross-national study of the 2015 PISA data involved more than 540,000 students in 72 OECD and partner countries. We used the publicly available PISA 2015 (OECD) data for Australia, Canada, Ireland, New Zealand, the UK, and the USA as well as the secure linked PISA 2015-NPD to and GCSE data from the same population of students in the UK to address participation, progression, achievement in and attitudes towards science. Both data sets have helped us address questions about the association of student levels factors (such as socio-economic status, gender, and ethnicity), school level factors (such as availability of science subjects, school type), interest and achievement.

The PISA data, available at https://www.oecd.org/pisa/data/2015database/ uses a two-stage sampling procedure, using schools, then students within schools to ensure a representative sample from the school population. The OECD-recommended procedure of using Balanced-Repeated-Replication (BRR) weights allowed us to produce descriptive and inferential statistics. We identified variables of interest to us (instructional approaches, affective aspects and achievement) along with students' background (number of books in their home, access to computer, parents' education level, occupation, etc.). Our focus in study one was on the six Anglophone countries, with 64,718 participants.

Table 1: Number of participating students from the Anglophone countries

Country	Number of participants
Australia	14,530
Canada	20,058
Ireland	5741
New Zealand	4520
United Kingdom (UK)	14,157
United States of America (USA)	5712

Of note, is the number of students from each country. In order to ensure that the sample for each country represents the school population, some countries 'oversample'. Each country identifies the school and aims to capture the full range of different demographics within the population. In the USA, which does not have a national education system, a smaller 'sub-national' sample was identified.

When we explored students' awareness of greenhouse gases, we used the larger data set, of 519,334 observations from 69 countries. Accounting for missing data and for countries whose students did not answer this question or other covariate questions (interest in broad science, parental occupation), the analysis, contained 336,396 students from 54 countries.

Approximately 540 000 students across the world completed the assessment in 2015, representing about 29 million 15-year-olds in the schools of the 72 participating countries and economies. PISA data are used to ‘rank’ countries, producing reports on student achievement in each of the three literacies, with a focus on science in 2015. These includes reports on interest and engagement in science, aspirations and career intent, associations between gender, immigrant status, socioeconomic background, affect and achievement as well as equity in education and report trends over time. These have policy implications for government and political jurisdictions, concerned about, for example, resources allocated to schooling, school attendance, learning time in science, effects of social deprivations and the learning environments of young people.

The National Pupil Database (NPD)

The NPD collects data about children and young people (age 2-21) maintained by the Department for Education and used nationally ‘for the purpose of promoting the education or wellbeing of children in England’ (DfE, 2013). Data collected includes students’ names and personal details (such as date of birth, disability, eligibility for free school meals, children in need status, school attendance, etc.) to track attainment and school examination and later university performance. Locally data are used to collect and analyse student-level information. Access to different sorts of data (such as KS2 and GCSE scores) is granted under strict, time-limited conditions in order to address very specific research questions. The matched dataset from the PISA 2015 and GCSE cohort of 2016 forms the smaller subset of the UK PISA cohort, the linked NPD-PISA dataset. This comprised more than 4000 participants, and we have been able to undertake a longitudinal study using prior high-stakes achievement at Key Stage Two, PISA, GCSE science grades and science ‘A’ level completion.

Exploring the relationship between instructional approaches and achievement

PISA scores are calculated from two-hour based computer tests using a combination of simple and complex multiple-choice and longer-response items. In addition, the student background questionnaire takes about 35 minutes to answer. All OECD countries used computer-based assessments and 15 partner countries used paper-based assessments. A snapshot of the data are provided to and within each participating country in the year following the administration of the assessment. The competencies of scientific literacy, *explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence scientifically* are assessed in local, national and global contexts, drawing on individual knowledge and attitudes towards science (for further information how these are explicit, please refer to the OCED PISA framework). All domains, (living, physical and earth and space systems) are assessed for content, procedural and epistemic knowledge and different levels of cognitive demand. Released items show how these questions 'fit' within the framework and examples are available through the OECD at https://www.oecd.org/pisa/test/PISA2015-Released-FT-Cognitive-Items.pdf.

To ensure that the assessment items were robust, fair and met the specifications of the PISA framework, a number of repeat items were used from 2006 (tracking items to monitor trends). Item response theory (IRT) methodology was used to develop a scale, and plausible values were calculated for all sampled students. The plausible values were transformed to a linear scale which are linked to both historical PISA scale and comparable across countries (OECD, 2017). The data are collected using a rotated test design in which students take overlapping tests with a view to gathering and reporting on population rather than individual students' proficiency. From these, an item map was constructed, levels of scientific literacy based on proficiency score points and recommendations made about how to use, analyse the data.

The mean PISA score, number of participating students and order of relative performance in PISA is shown in table 2.

Table 2: Science literacy performance in PISA 2015 for six Anglophone countries (Australia, Canada, Ireland, New Zealand, the United Kingdom & the United States)

Country	N of cases	Mean	SE	95% confidence interval	Range of ranks among OECD countries	
					Upper rank	Lower rank
Australia	14,530	510	1.54	507 - 513	6	11
Canada	20,058	528	2.08	524 - 532	3	4
Ireland	5,741	503	2.39	498 - 507	11	18
New Zealand	4,520	513	2.38	509 - 518	5	9
UK	14,157	509	2.56	504 - 514	6	13
USA	5,712	496	3.18	490 - 502	15	25

Note. Table adapted from OECD, 2016a, *PISA 2015 Results (Vol. I)*.

Among 32 OECD countries, Canada's rank in science literacy could potentially range between third and fourth. Showing considerably more variability, students' science literacy mean for the UK could place it between 6th and 13th among OECD countries. Students in the USA show both the lowest science literacy mean and the largest variability in science literacy among the six countries examined.

How PISA conceptualises classroom instruction

The way in which science is taught can influence how interested, engaged and informed students are, and teachers are responsible for the delivery of currculum content as well as shaping views towards, beliefs about and 'trust' in science. Different instructional approaches are used by teachers as they work with their students and in PISA 2015, students were asked about the frequency of certain activities ('never or almost never', 'some lessons', 'many lessons' or 'every lesson or almost every lesson') during their science lessons.

For the 2015 round, PISA developed four constructs of instructional practices using students' responses to the 2006 assessment. These constructs, each a compound variable, are adaptive instruction (ADINST), inquiry-based instruction (IBTEACH), and teacher-directed instruction (TDTEACH), as well as perceived feedback (PF). This approach to classifying instructional approaches is not without its problems or critics. Some items within the compound variable are similar to the constructs that were used in earlier PISA rounds (2006), and others were newly developed for use in 2015. In this study, we have focused on three teaching strategies, IBTEACH, TDTEACH and ADNIST. Each of these teaching strategies or approaches are not mutually exclusive, and the student responses tell us very little about the quality of the different approaches, reporting on *frequency* of each of the items making up the variables.

For **adaptive instruction**, students were asked how frequently their teacher adapts the lessons based on students' needs. PISA constructed this variable (ADINST) from students' reports on three survey items about teacher activities in science classrooms. These included: *the teacher adapts the lesson to my class's needs and knowledge*; *the teacher provides individual help when a student has difficulties understanding a topic or task*; and, *the teacher changes the structure of the lesson on a topic that most students find difficult to understand*. Taking these items together, this index of adaptive instruction could also be characterised as 'differentiated instruction' (OECD, 2016a, 2016b).

The composite variable **inquiry-based instruction** included questions about experimentation and hands-on activities as well as developing conceptual understanding of scientific ideas. PISA constructed this variable or index of inquiry-based instruction (IBTEACH) from students' responses to nine survey items about the frequency with which they experienced specific activities. These included: (1) *students are given opportunities to explain their ideas*; (2) *students spend time in the laboratory doing practical experiments*; (3) *students are required to argue about science questions*; (4) *students are asked to draw conclusions from an experiment they have conducted*; (5) *the teacher explains how a science idea can be applied to different phenomena*; (6) *students are allowed to design their own experiments*; (7) *there is a class debate about investigations*; (8) *the teacher clearly explains the relevance of science concepts*; and, (9) *students are asked to do an investigation to test ideas* (OECD, 2016a, 2016b).

For **teacher-directed science** instruction, students were asked about the frequency of, *The teacher explains scientific ideas; A whole class discussion takes place with the teacher; The teacher discusses our questions*; and *The teacher demonstrates an idea*. Combined student responses provide an index of TDTEACH, where higher values indicate more frequent use of this approach. As for the teaching of mathematics, this approach is used more frequently that others in science and is often referred to as 'traditional' teaching. When students report that *the teacher explains scientific ideas*, in many or every lesson, students' PISA scores are 28 points higher. In OECD countries, this approach is more commonly used in more economically advantaged schools.

Cross-national study

Firstly, we report on the comparative study which explored the six Anglophone countries. We chose these six because they arguably have had substantial exposure to inquiry-based teaching and learning as preferred pedagogy in school science, and because they share broadly similar systems of comprehensive secondary schooling, similar socio-cultural roots, and similar economic and government systems.

Statistics in the cross-national study were produced using the International Database (IDB) Analyzer, an application developed by the International Association for the Evaluation of Educational Achievement (IEA) that can be used to analyse most major large-scale assessment surveys, including those conducted by the OECD. Additionally, when possible, we retrieved descriptive statistics directly from the publicly available primary analysis of PISA 2015 conducted by the OECD (OECD, 2016a, 2016b). The benchmark analyses were produced with the IDB Analyzer using a BRR procedure (Fay variant) with 80 replications (OECD, 2009). Benchmarks reflect PISA's differentiated levels of science literacy (OECD, 2016a); for 2015 there were 8 levels, but for our purposes the two at either end of the science literacy distribution were collapsed into one to achieve more robust numbers of students represented at each level. The figures depicting the benchmark analyses therefore use 6 benchmarks (or levels) of science literacy performance.

Each of the compound variables representing instructional strategies, (ADINST, IBTEACH, TDTEACH) are called to a mean of zero and a standard deviation of one. The three indices represent students' aggregated reports of the frequency with which they experience the classroom activities that comprise each pedagogical approach.

The patterning of country groupings changes for students' experiences of teaching approaches. For adaptive instruction (ADINST), students in Australia, Canada, New Zealand, and the USA report mean levels of adaptive instruction well above the international mean (in all cases, about one quarter of a standard deviation above). Students in the UK report a slightly more modest occurrence of adaptive instruction, and students in Ireland report adaptive instruction at a level consistent with the international mean. Although having notably different science literacy means, students from Canada and the USA report similar frequencies of inquiry-based teaching and learning (IBTEACH) in science, *considerably above* the international average. Australian and New Zealander students, in contrast, report inquiry-based activities *moderately* above the international average, and students in Ireland and the UK report experiencing inquiry in secondary science classrooms essentially *equal to the scaled international mean*.

Table 3: Student-reported science teaching activity means and standard deviations for six Anglophone countries (Australia, Canada, Ireland, New Zealand, the United Kingdom & the United States of America)

	ADINST (adaptive instruction)			**IBTEACH (inquiry-based)**			**TDTEACH (teacher directed)**		
	Mean	SE	SD	Mean	SE	SD	Mean	SE	SD
Australia	0.20	0.01	0.95	0.18	0.01	0.84	0.27	0.01	0.99
Canada	0.26	0.02	1.01	0.27	0.01	0.97	0.37	0.01	1.06
Ireland	-0.02	0.02	0.95	0.01	0.02	0.80	-0.02	0.02	0.93
New Zealand	0.25	0.02	0.93	0.16	0.02	0.86	0.29	0.02	0.98
UK	0.15	0.02	0.97	-0.01	0.01	0.84	0.09	0.01	0.94
USA	0.24	0.02	1.01	0.34	0.03	1.04	0.32	0.02	1.07

A similar pattern is apparent for teacher-directed teaching and learning in science (TDTEACH). Students in Canada and the USA report the highest frequencies, on average, of teacher-directed activities in science, both considerably above the international average (0.37 for Canada, and 0.32 for the USA, respectively; about one-third of a standard deviation higher than the scaled mean). Students in Australia and New Zealand report slightly more modest frequencies of teacher-directed activities in science (0.29 for New Zealand and 0.27 for Australia, respectively), and students in Ireland and the UK and report teacher-directed activities at the international mean.

This shows the mean frequencies reported by students. In order to explore associations of reported instructional strategies with the student PISA score, we mapped the frequency of each variable against the benchmark or levels of scientific literacy.

Figure 1: Mean Levels of Adaptive Instruction at Six Science Literacy Performance Benchmarks for Students in the Anglophone Countries in PISA 2015

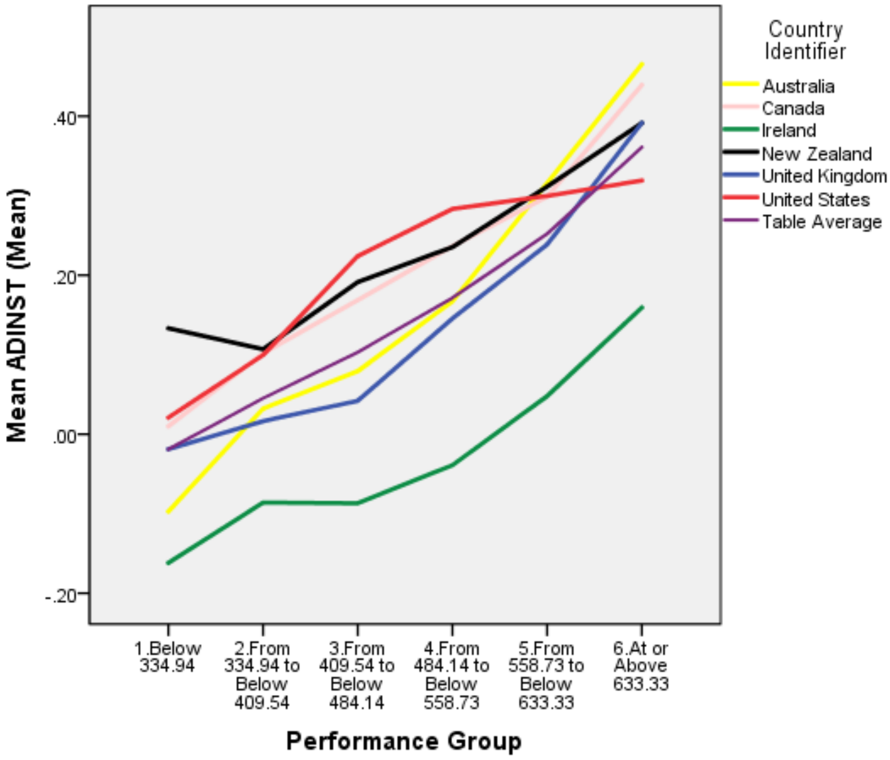


Figure 2: Mean Levels of Inquiry-Based Teaching at Six Science Literacy Performance Benchmarks for Students in the Anglophone Countries in PISA 2015

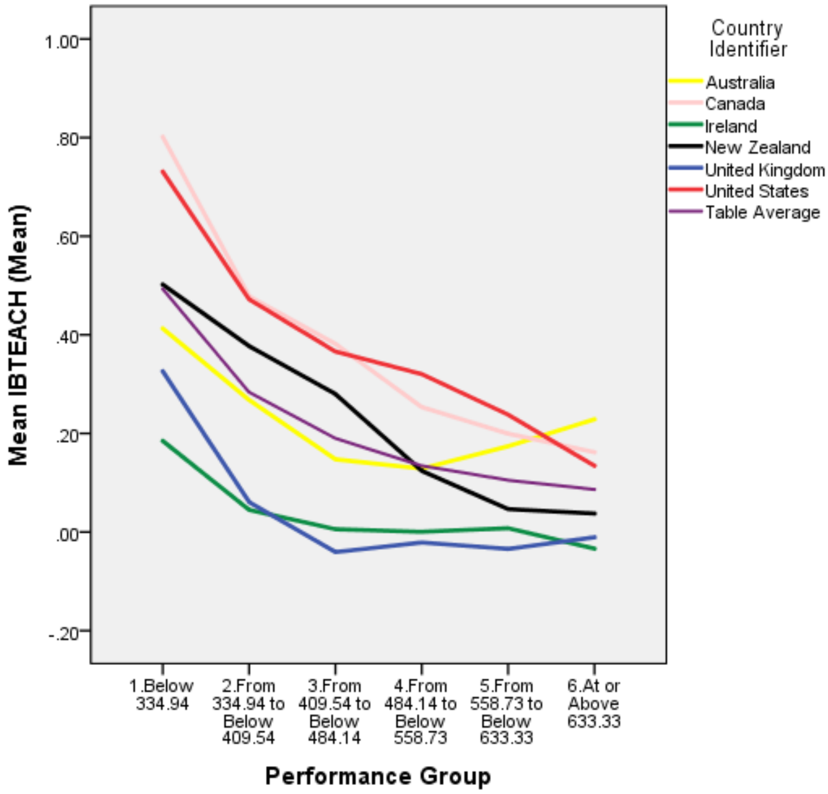
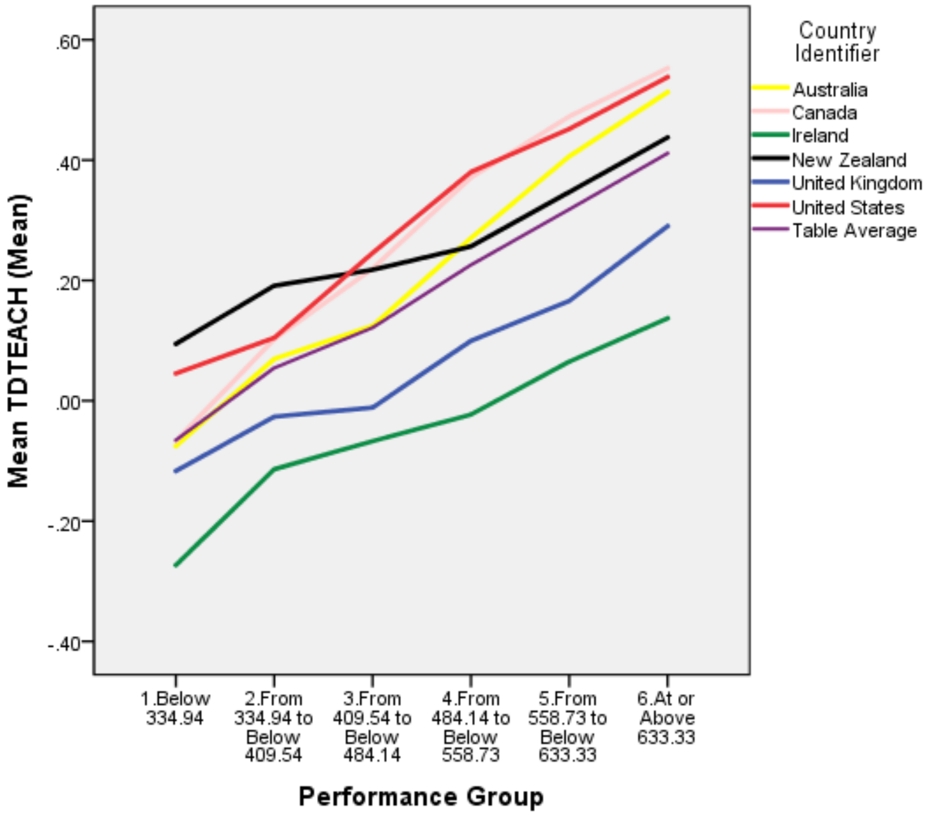


Figure 3: Mean Levels of Teacher-Directed Instruction at Six Science Literacy Performance Benchmarks for Students in the Anglophone Countries in PISA 2015



Figures from Oliver, M., et al. (2021). The Efficacy of Inquiry-Based Instruction in Science: a Comparative Analysis of Six Countries Using PISA 2015. *Research in Science Education.*

These graphs show consistent patterning of student responses, and point to an association between achievement and instructional strategies. Whereas higher frequencies of students' reports of adaptive teaching and teacher-directed instruction are associated with higher levels of scientific literacy, we find the reverse is the case of inquiry-based teaching. In all six Anglophone countries in this study, students at the lower levels of science literacy performance are consistently those who tend to report the highest frequencies of inquiry-based activities. Students performing at higher levels of scientific literacy are those who also report lower levels of inquiry in their science classrooms. As students' home backgrounds are likely influences on their achievement, we wanted to tease out the effects of home background and we conducted a multivariate regression analysis using the IDB Analyzer, to examine the direction and relative size of the effect on science literacy for each instructional approach. In doing this, we accounted for students' socioeconomic status, and controlled for the other two instructional approaches.

The index of economic, cultural and social status (ESCS) is a measure that PISA has developed and can be broadly conceptualised as,

> *ESCS is a measure of students' access to family resources (financial capital, social capital, cultural capital and human capital) which determine the social position of the student's family/household* (Avvisati, 2020, p. 1).

Whilst 'education, income and occupation' are likely to inform this index, PISA gathers information about students' background to construct ESCS using highest parental education, highest parental occupation, and home possessions (including books in the home), family wealth and cultural possessions and home educational resources. The technical report (OECD, 2017) shows Cronbach's alpha, a measure of reliability for standardised variables. 'Parental education' is now aligned with ISCED and as the ESCS model has evolved over the PISA cycles, these are not comparable directly across cycles.

Table 4: Multivariate (simultaneous solution) regression coefficients for the PISA score on three instructional approaches

	CONSTANT (a)	**ESCS (b_1)**	**ADINST (b_4)**	**IBTEACH (b_2)**	**TDTEACH (b_3)**
Australia	508.47	38.62	11.83	-15.13	11.72
Canada	518.03	31.42	7.56	-17.08	10.46
Ireland	504.67	35.53	6.64	-13.44	9.75
New Zealand	519.12	42.81	9.77	-25.68	10.74
UK	508.62	36.24	12.65	-15.49	8.07
USA	499.94	31.98	4.31	-15.83	11.57

Notes. $\hat{Y}$ PISA score = a + b_1ESCS + b_2IBTEACH + b_3TDTEACH + b4ADINST
All regression coefficients in Table 4 are statistically significant ($p < 0.05$).

Countries have different ways of determining indices of relative wealth and affluence, such as 'free school meals' and PISA uses a global index capturing a limited number of indicators that meaningfully represent socioeconomic status. Socially advantaged student perfume better in PISA than their less advantaged peers. Students' socioeconomic status (ESCS) explains a large proportion of the variance in the PISA scores, measuring scientific literacy, varying between 31.98 and 42.81 points difference across the six countries considered here.

Generally, for these six countries the patterning evident from benchmark analysis suggests a *negative relationship* between the frequency of inquiry-based activities and students' literacy in science. This confirms the findings of studies across other countries (for example, Cairns & Areepattamannil, 2019; Jiang & McComas, 2015; Lau & Lam, 2017). Counter-intuitively, such 'student-centred' teaching approaches are found to be negatively associated with student achievement (Gocorova, Benítez & Muñiz, 2020).

Together these finding have met with some criticism and reflection. Does the PISA measure of 'inquiry' capture what is an exploration of the nature of science, procedural and cognitive aspects of teaching and learning science? How can we explain the negative associations between inquiry and achievement in large-scale international assessments? How do these findings sit in the context of a science education literature that largely endorses and support teachers to use more inquiry in classrooms? It is suggested that successful implementation of inquiry strategies requires professional learning support and development, and such opportunities may not be widely 'available for teachers in the average school' (Aditomo & Klieme, 2020, p.6). Other explanations advanced have considered the level of guidance offered by the teacher or the structure of inquiry as part of the lesson(s). Here, a meta-analysis of inquiry-based science teaching offers some insight, as '*engaging students in guided inquiry contexts does lead to learning gains when contrasted with comparison groups featuring traditional lessons or unstructured student-led activities*' (Furtak et al., 2012, p. 324). As others have noted (Cairns & Areepattamannil, 2019; Lau & Lam, 2017), the PISA construct of 'inquiry' is loosely operationalised and presented as '*about engaging students in experimentation and hands-on activities, and also about* *challenging students and encouraging them to develop a conceptual understanding of scientific ideas*' (OECD, 2016b, p. 69) comprising items that may appear contradictory.

Some researchers have recoded aspects of the compound variable of inquiry (IBTEACH) into two, the *interactive investigative* and the *interactive application* and reported differential associations between each of these and students from the top performing PISA countries. The *interactive investigative* 'construct was found to have a negative association with science performance' (Lau & Lam, 2017, p. 2142). Others have disaggregated the PISA inquiry variable into *guided, transmissive* or *independent* (Aditomo & Klieme, 2020) reporting that more guided forms of inquiry are associated with higher levels of student achievement. In the next part of our analysis, we looked the disaggregated variable to explore any association between these and the student PISA score.

In order to determine if there was a differential effect of individual items on the student PISA score, we examined each of items of the inquiry constructs (IBTEACH) and the frequency with which students reported experiencing specific aspects of inquiry in the science lessons.

Figure 4: Associations between the PISA score (scientific literacy) and items of the inquiry variable (IBTEACH)

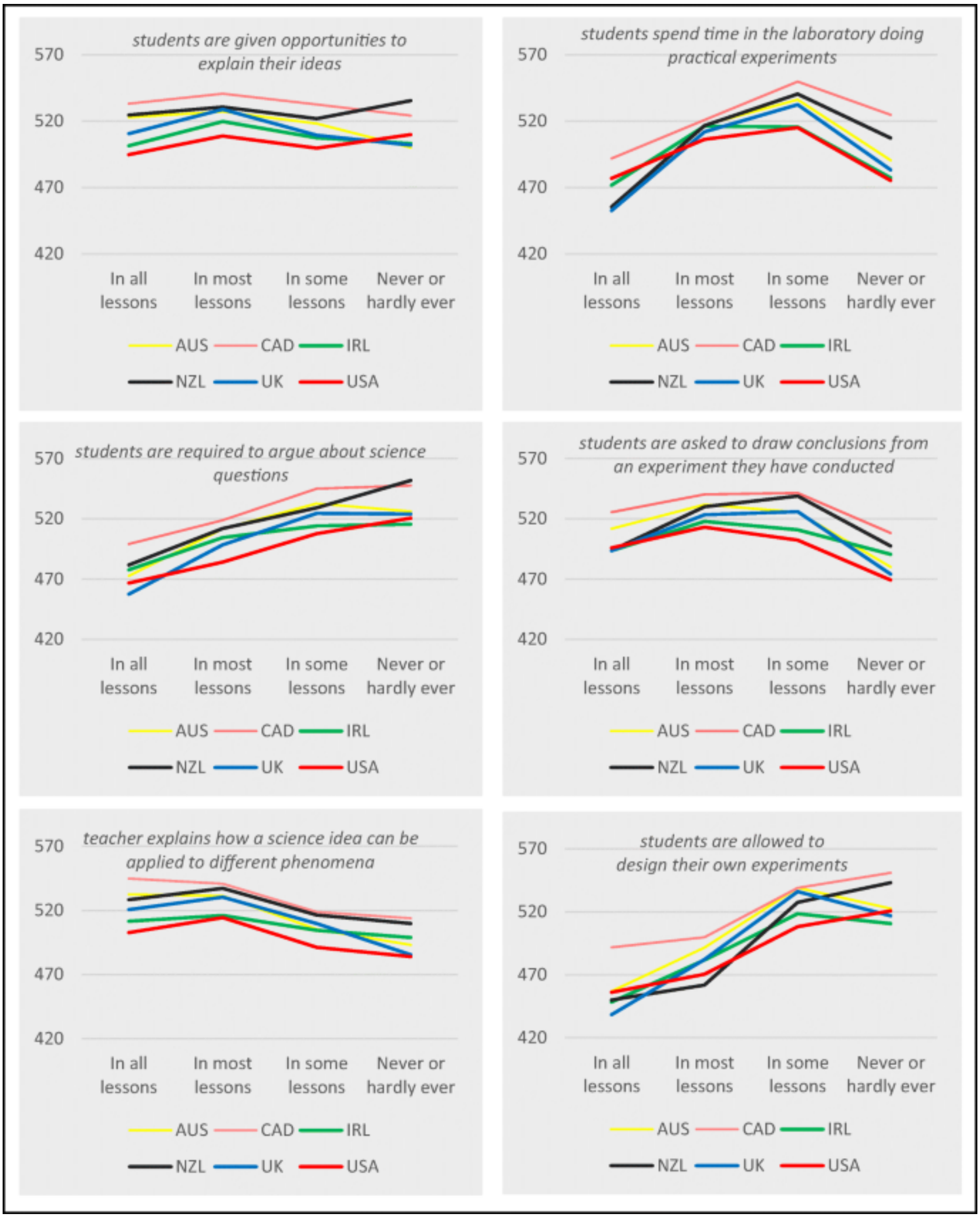


Figure adapted from Oliver, M., et al. (2021). The Efficacy of Inquiry-Based Instruction in Science: a Comparative Analysis of Six Countries Using PISA 2015. *Research in Science Education.* A more complete analysis of this disaggregated variable is available in the published paper, https://doi.org/10.1007/s11165-019-09901-0.

There are three main sets of associations from these data. Firstly, where there is no apparent relationship between the inquiry item and the student PISA score, such as when *students are given the opportunity to explain their ideas*. Secondly, there is a negative and linear relationship between the frequency of the inquiry item and the PISA score, such as where *students are required to argue about science questions.* Finally, we note a curvilinear relationship between frequency and student score for the items including *spending time in a laboratory doing practical work* and *drawing conclusions from an experiment they have conducted.* Both of these items constitute what many teachers would recognise as 'inquiry'. Of particular note is that the highest level of student achievement is associated with doing practical work in *some* lessons (rather than *all* or *most*) and this patterning is consistent across all six countries. Doing practical work in *each lesson* or *very rarely* are both unlikely to support the development of scientific literacy. In learning science, undertaking and developing experimental work is important and can support students' skill acquisition, learning and interest in science (Sjøberg, 2018). Two items especially deserve greater attention: when students report *spending time in the laboratory doing practical work* during *some* lessons and *drawing conclusions from an experiment they have conducted* in *most* lessons, these may represent a 'sweet spot' of strategy and achievement. Similar patterning is observed using TIMSS data to explore instructional strategies and achievement in Grade Eight students in Norway, where a curvilinear relationship is reported between frequency of inquiry strategies and student achievement (Teig et al., 2018).

Not only is 'inquiry' more complex than is sometimes presented, and rather than advocate or criticise inquiry *per se*, this study shows that educators focus on the purpose of using inquiry approaches in teaching science. Finding that students who are 'low achieving' experience higher levels of inquiry raises questions about classroom practices: are they low achieving because of high inquiry or is that pedagogical approach used to provide interest, engagement and motivation where a more didactic approach would not? Are lower-achieving students 'missing out' on developing their scientific literacy by engaging in largely procedural aspects of inquiry? We do not know. Finding that '*highly student-driven dimensions of inquiry, particularly procedural activities associated with investigation, are least frequently associated with high levels of student science achievement'* (Forbes, Neumann & Schiepe-Tiska, 2020, p. 801) is observed across different countries that include those above, at, or below the OECD mean level for scientific literacy. A likely recommendation from the analysis of these data is that '*well-planned, scaffolded, open-inquiry approaches that directly support students with the underlying processes used to independently generate science knowledge'*.

While inquiry-based teaching and learning hold different meanings for different stakeholders, PISA's constructed composite variable reflects a relatively broad spectrum of pedagogical strategies arguably associated with the approach. We have shown here that specific aspects of inquiry might be more (or less) associated with student achievement and this is observed in other analyses of large-scale studies (Cairns, 2019; Capps & Crawford, 2013; Forbes et al., 2020; Furtak, et al., 2012; Lau & Lam, 2017).

GCSE and PISA scores in England

The linked NPD-PISA data set enabled us to undertake a longitudinal study to explore associations between KS2, GCSE and the PISA score of scientific literacy. Ministerial comments that the '*most effective, teacher-led practices should be twinned with a knowledge-rich curriculum. That is how evidence can and should be turned into policy, action and change'* (Gibb, 2017). These have been interpreted as promoting greater 'direct instruction' in schools. Critics argue that these more traditional methods of teaching are out of place in schools and more student-led, inquiry approaches are more appropriate.

For the first time, the linked NPD-PISA data are used to address three questions of English students' achievement and their experiences in learning science at school. Firstly, how is frequency of experiencing inquiry-based teaching associated with achievement? Secondly, how are specific components of the inquiry variable (IBTEACH) associated with achievement, and thirdly, how are guided approaches associated with achievement? In undertaking this analysis, we have been able to draw on student prior achievement (KS2 data), and their performance on 'high stakes' examinations, the GCSE. Unlike the PISA scores, achievement at GCSE (taken some six months later than PISA) is individually reported and can be a strong determinant of further academic studies, life choices and career direction.

Students in England are able to take a variety of science courses at GCSE (separate, double and triple) so to account for this, the statistical model accounts and controls for the science course and the 'science pillar score' is used. In this national study, the primary outcome measure used is the GCSE score and the PISA score as a secondary outcome. While PISA explicitly assesses students' scientific (and other) literacy, the science GCSE focus serves other purposes.

In exploring inquiry for this study, two of the PISA items have been omitted ('*the teacher explains the application of science'* and the '*teacher explains the relevance of science'*) as they do not align with the US National Science Education Standards and it can be argued that these are closer to a more teacher-led instruction rather than inquiry. These selected seven items correlate (0.95) with the PISA IBTEACH scale. Then we divided these into four discrete groups of 'frequency of inquiry-based teaching' with the bottom being infrequent, the top being most frequent.

Table 5: Descriptive statistics showing how frequency of inquiry-based teaching is associated with GCSE and PISA scores

	Inquiry-based teaching quartile			
	Bottom quartile	**Q2**	**Q3**	**Top quartile**
Average GCSE grade	5.18	5.37	5.56	5.21
Average PISA score	513	529	538	503
Key Stage 2 level	4.3	4.3	4.38	4.23
% Female	58%	53%	48%	41%
SES index (standardised)	-0.04	-0.02	0.05	0.09
% Ever FSM eligible	24%	24%	23%	26%
% Triple science	22%	29%	35%	30%

Notes: Top (bottom) quartile refers to the most (least) frequent use of inquiry-based teaching methods. Key Stage 2 level = a measure of science attainment aged 11.

SES index = a composite measure of socio-economic status. % FSM eligible = a school-level measure of eligibility for Free School Meals. % Triple science = proportion of students taking three separate science qualifications at age 16.

From this table, we note that prior achievement (KS2) and the measure for school-level deprivation show little relationship with inquiry. However, the *student-level* deprivation measure (SES index) shows a clear positive relationship with inquiry, and females reported a lower level of inquiry than males. Students in the middle two quartiles of inquiry have the highest attainment levels on both PISA scores and GCSE grade. This finding supports the emerging consensus of a non-linear relationship between frequency of inquiry and student achievement (Teig et al., 2018).

In considering teacher guidance, we suggest that this is best represented when teachers model a solution, provide cues, or direct students to attend to specific information. In capturing levels of teacher guidance using the PISA questionnaire, many have used some of the well-theorised PISA items in two separate scales to explore guidance offered to students. Teacher guidance is thought to confer benefits in terms of reduced student cognitive load (Hmelo-Silver, Duncan, Chinn, 2007; Sweller, Ayres, Kalyuga, 2011). To determine any association between our inquiry-based teaching scale and the students' achievement (using the science pillar scores from GCSE), a series of Ordinary Least Squares regression models were constructed that captured inquiry, prior achievement, specific demographic and school level controls.

$$GCSE_{ij} = \alpha + \beta.IBTEACH_{ij} + \gamma.D_{ij} + \delta.PISA_{ij} + \tau.KS2_{ij} + \sigma.Course_{ij} + \theta.Scales_{ij} + \mu_j + \varepsilon_i \qquad (1)$$

Where:

- $GCSE_{ij}$ = Student GCSE science grades. This has been measured via the science pillar points score, and has been standardised to mean zero and standard deviation 1.

- $IBTEACH_{ij}$ = A set of dummy variables referring to quartiles of the inquiry-based teaching scale. The bottom quartile (infrequent use of inquiry-based teaching) has been set as the reference group.
- D_{ij} = A vector of demographic characteristics (e.g. gender, socio-economic status, immigrant group).
- $Course_{ij}$ = A vector of controls for the type of science course the student is enrolled in at school (e.g. triple science, double science etc).
- $PISA_{ij}$ = Student scores on the PISA science test, including the 'content' sub-domains[1].
- $KS2_{ij}$ = Key Stage 2 mathematics point score, reading point score and teacher-assessed science level.
- $Scales_{ij}$ = A vector of controls for other factors that potentially impact upon their GCSE science grades, but are not themselves likely to be influenced by inquiry-based teaching practices.
- μ_j = School-fixed effects.
- i = Student i.
- j = School j.
- ε_i = Error term. All estimates account for the clustered sample design via a Huber-White adjustment being made to the standard errors.

Four models are presented in Table 6. Model 1, for example, includes demographics such as gender, socioeconomic status and immigrant status). In this model, we note a small but moderate association between frequency of inquiry-based teaching in the second and third quartiles and achievement. However, we see no difference in GCSE grades between those who receive a little or a lot of inquiry-based teaching.

[1]In our models we control for all ten plausible values. This provides the most extensive possible control using the PISA data for each child's ability in science.

Table 6: Estimated association between inquiry-based teaching and students GCSE science grades

	Model 1		Model 2		Model 3		Model 4	
	Effect	**SE**	**Effect**	**SE**	**Effect**	**SE**	**Effect**	**SE**
Inquiry-teaching scale								
Bottom quartile (Reference)	Reference		Reference		Reference		Reference	
Second quartile	**0.11***	**0.04**	**0.06***	**0.03**	**0.05***	**0.02**	0.02	0.02
Third quartile	**0.16***	**0.04**	**0.09***	**0.03**	**0.06***	**0.03**	0.02	0.03
Top quartile (extensive use)	-0.05	0.04	**0.10***	**0.03**	**0.10***	**0.03**	0.06	0.03
Observations	**4,361**		**4,361**		**4,361**		**4,361**	
Controls								
Demographics	Yes		Yes		Yes		Yes	
Key Stage 2 scores	-		Yes		Yes		Yes	
PISA science scores	-		Yes		Yes		Yes	
Science subjects studied	-		Yes		Yes		Yes	
School fixed effects	-		-		Yes		Yes	
Science study minutes	-		-		-		Yes	
Sense of belonging	-		-		-		Yes	
Test anxiety	-		-		-		Yes	
Parent emotional support	-		-		-		Yes	
Before school activities	-		-		-		Yes	
After school activities	-		-		-		Yes	
Perception teacher fairness	-		-		-		Yes	

Notes: All figures can be interpreted in terms of effect sizes. SE = Standard Error. Bold coefficients with * indicate statistical significance at the five percent level.

Including prior achievement and PISA scores into Model 2, we see a small positive effect between frequency of inquiry-based teaching and progress made in the GCSE year. This difference amounts to approximately one tenth of a GCSE grade. Adding in school-level controls, into Model 3, we see no overall association between inquiry-based teaching and achievement. Finally, in Model 4, once additional items have been included (such as students' sense of belonging, test anxiety, parental emotional support, etc.), we find no difference in GCSE grades between students who receive little inquiry-based teaching (the bottom quartile) and this who receive a lot (top quartile). When we looked at this more closely, we concluded that there is evidence that frequency of inquiry-based teaching has little impact upon students' performance in their GCSE science exams. (Jerrim et al. 2019).

As well as conducting the analysis using the final PISA inquiry-based teaching scale, we also provide a breakdown of estimates using each individual question. With the question '*students are allowed to design their own experiments',* we re-estimated equation (1) removing the IBTEACH variable and including students' responses to this question in its place. This was repeated for each of the nine items that form the inquiry-based teaching scale (listed above), to identify if any aspect type of inquiry-based classroom activity has a particularly strong association with science attainment growth (between PISA and GCSE). These data are shown in Table 7.

Table 7: Estimated association between different types of inquiry-based teaching practices and students GCSE science grades

	Some			**Most**			**Every**		
Items	**%**	**Effect**	**SE**	**%**	**Effect**	**SE**	**%**	**Effect**	**SE**
1. Explain ideas	20%	-0.03	0.05	38%	-0.03	0.04	37%	0.00	0.05
2. Practical experiments	62%	0.04	0.03	**15%**	**0.09***	**0.04**	4%	0.06	0.06
3. Argue about science questions	37%	0.02	0.02	12%	-0.04	0.03	5%	0.05	0.05
4. Conclusions from experiments	45%	0.05	0.04	36%	0.07	0.04	12%	0.05	0.04
6. Design experiments	30%	0.01	0.02	6%	0.00	0.04	3%	0.08	0.05
7. Class debate	33%	0.02	0.02	11%	-0.02	0.03	4%	0.09	0.06
9. Investigations to test ideas	51%	0.04	0.03	**22%**	**0.07***	**0.03**	8%	0.07	0.05

Notes: All figures can be interpreted in terms of effect sizes, with the 'never' category as the reference group. Percentages refer to the percentage of students within the 'some', 'most' and 'every' group. SE = Standard error. * indicates statistical significance at the five percent level. Estimates all based upon model specification 4 (see Table 6). Full version of questions are as follows: 1= *Students are given opportunities to explain their ideas. 2 = Students spend time in the laboratory doing practical experiments. 3 = Students are required to argue about science questions. 4 = Students are asked to draw conclusions from an experiment they have conducted. 6 = Students are allowed to design their own experiments. 7 = There is a class debate about investigations. 9 = Students are asked to do an investigation to test ideas*. Items 5 and 8 from the original PISA IBTEACH scale were excluded

The analysis enabled us to explore the effects of inquiry-based teaching on different groups of students (such as gender, high-achieving students, etc.) but we find that all estimated effects are small and do not reach the statistical significance. Even in classrooms where there is good disciplinary climate, the difference in achievement between students in the top and bottom quartiles is small, with an effect size of 0.1. When we looked instead at using PISA as the primary outcome measure, here, we note the significant finding that the relationship is negative - that students reporting high frequency of inquiry-based teaching tend to have lower PISA scores.

There is theoretical justification for focusing on teacher guidance (Kirschner et al., 2006; Hmelo-Silver et al., 2007), based on the idea that higher levels of guidance and scaffolding may reduce the cognitive demands of inquiry-based learning, helping students to focus limited working memory capacity on the most pertinent aspects of the learning experience. There is also some evidence from empirical studies of teaching which suggests that guidance is an important moderator of the efficacy of inquiry-based methods (Aditomo & Klieme, 2020; Furtak et al., 2012; Lazonder & Harmsen, 2016).

In order to investigate this, we split the students in the data into two groups (low and high) based on their responses to a number of questions indicating the degree of guidance. These questions ask for pupils to rate the frequency with which the following types of guidance occur, on a four-point scale from ‘Every lesson’ to ‘Never or hardly ever’:

1. *The teacher gives students extra help when they need it*
2. *A whole class discussion takes place with the teacher (reverse coded)*
3. *The teacher tells me how to improve my performance*
4. *The teacher advises me how to reach my learning goals*

Table 8: Estimated association between different types of teacher guidance and students GCSE science grades

Guidance Measures	Low Guidance			High guidance		
	Q2	Q3	Q4	Q2	Q3	Q4
The teacher gives students extra help when they need it	0.12	-0.04	0.02	0.04	**0.08***	0.05
	(0.06)	(0.09)	(0.11)	(0.04)	(0.03)	0.04
A whole class discussion takes place with the teacher	0.04	0.05	0.00	0.09	**0.20***	**0.19***
	(0.04)	(0.04)	(0.05)	(0.07)	(0.06)	(0.07)
The teacher tells me how to improve my performance	0.03	0.06	0.03	0.06	**0.12***	**0.11***
	(0.04)	(0.04)	(0.05)	(0.06)	(0.06)	(0.06)
The teacher advises me how to reach my learning goals	0.04	0.04	0.05	0.07	**0.15***	0.10
	(0.04)	(0.04)	(0.05)	(0.06)	(0.05)	(0.05)

Notes: All coefficients can be interpreted in terms of effect sizes, with the lowest discovery quartile as the reference group. Standard errors are shown in parentheses and have been clustered at the school level. Bold coefficients with a * indicate $p<0.05$. Estimates all based upon model specification 4 (see Table 1 for further details on controls included).

The analysis shows no relationship between any quartile of inquiry-based teaching for the students reporting low levels of teacher guidance. Among the students reporting high guidance however, the third and fourth quartile of inquiry is associated with increased attainment, with effect sizes ranging between 0.08 and 0.2. Interestingly, the coefficients are slightly larger in the third quartile than in the fourth. In summary, neither high inquiry with low guidance, or high guidance with low inquiry are related to improved GCSE science attainment; but high inquiry and high guidance are. This pattern of results, which is consistent with theory and existing evidence, is suggestive that guidance moderates the relationship between inquiry and attainment (Furtak et al., 2012; Rönnebeck et al., 2016) and supports the emerging consensus that teacher-guided inquiry can lead to positive cognitive and affective outcomes (Aditomo & Klieme, 2020).

Exploring the relationship between ‘affect’ and achievement

It is long assumed that positive attitudes augur well for achievement, with early interest in science (Maltese & Tai, 2010; Mourshed, Krawitz, & Dorn, 2017) and intent to pursue science beyond school level (DeWitt, Osborne, Archer, Dillon, Willis & Wong, 2013; Sheldrake, Mujtaba, & Reiss, 2017). At the same time, the ‘soft’ or non-cognitive aspects have been rarely explored in policy reports about influences on students’ achievements. Increasingly, evidence is accumulating that non-cognitive factors exert considerable effect on academic achievement (McGill, et al., 2019) although there has been ‘little consensus on whether the relationship between non-cognitive skills and later outcomes’ is robust, transient or causal (Gutman & Schoon, 2013, p. 4). Is time spent on homework a proxy for a student’s ‘motivation and engagement’ (Sammons et al., 2014, p. 112) or ought we encourage a focus on effort, time management and study strategies (Rogers, 2013)?

Affective measures include attitudes or disposition towards, motivation, enjoyment and interest in science. These may underpin individuals’ competences to ‘explain phenomena, evaluate scientific design and inquiry, and interpret data and evidence scientifically’ (OECD, 2017, p.25). While these rarely feature in headline news, a goal of science education is to develop attitudes that lead students to engage with scientific ideas, to be informed and critical users of scientific knowledge, not only to help young people to become the next generation of scientists. These were operationalised to include ‘interest in science and technology, environmental awareness and valuing scientific approaches to inquiry’ (OECD, 2017, p.2).

While enjoyment of science has been associated with participation in science, teachers are keen to maintain interest, enthusiasm and engagement with science. As Aditomo and Klieme (2020) have remarked, it may be that teachers respond to students through adapting their own teaching strategies. Although reported to decline as they progress through school (Archer et al., 2010), the PISA data show high levels of interest in fifteen-year old students in the Anglophone countries with similar patterns of responses. In the broader context these data are positive as all these countries showed greatest positive changes from 2006 when students were last surveyed (OECD, 2016b). All except the USA showed positive changes from 2006 in students' instrumental motivation to learn science, which suggests that students have thought about their reasons for studying science.

Table 9: Percentage of students enjoying science in the Anglophone counties

Country	I generally have fun when I am learning science	I like reading about science	I am happy working on science topics	I enjoy acquiring new knowledge in science	I am interested in learning about science
Australia	65	53	67	72	67
Canada	75	63	69	79	79
Ireland	64	56	71	78	74
New Zealand	66	52	71	76	72
UK	67	52	72	72	69
USA	72	57	69	76	73

Data from OECD, 2016 b

Across all countries surveyed, interest in and enjoyment of science were positively related to student achievement (OECD, 2016 b) with the findings that in every economy '*the 25% of students who reported the most enjoyment scored higher than the 25% of those who reported the least enjoyment'* (OECD, 2016, p. 133). A one-unit increase in enjoyment of science is associated with large score point difference (of 33 points for Australia, 27 points Canada, 32 points in Ireland, 32 points in New Zealand, 30 points in UK, and 26 points in USA). These are statistically large effects.

Attitudes to and interest in science decline during adolescence (Bennett & Hogarth, 2009; Osborne, Simon & Collins, 2003) and the fifteen-year-olds in this data set are assumed to be representative of the larger cohort. In this study, we use some of the non-cognitive, or affective, and student-level variables to explore the impact of these and instructional strategies on academic performance of the fifteen-year olds in England. Engagement, the 'holy grail of learning' (Sinatra, Heddy & Lombardi, 2015,

p. 1), comprises behavioural, cognitive and emotional dimensions. In PISA, this construct is operationalised to include interest in, enjoyment and joy of science, instrumental and achieving motivation. As an example, 'Interest in Science' was measured in the 2015 student questionnaire by exploring,

- *A curiosity in science and science-related issues and endeavours;*
- *A willingness to acquire additional scientific knowledge and skills, using a variety of resources and methods;*
- *An on-going interest in science, including consideration of science-related career*s. (OECD, p. 37).

Interest in science was assessed with two scales - interest in broad science and enjoyment of science. Interest is thought to be a 'relatively stable and enduring personal emotion' (Cheung, 2018, p.1) which emerges in early childhood (Maltese & Tai, 2010; Royal Society, 2014). Attitudes towards science may be related to a belief in ones' ability to be successful in science, or science self-concept (Cheung, 2018), interest and motivation to study science. PISA 2015 used the same meaning of interest to explore interest in science. Details of the items used to construct these variables are in Appendix B.

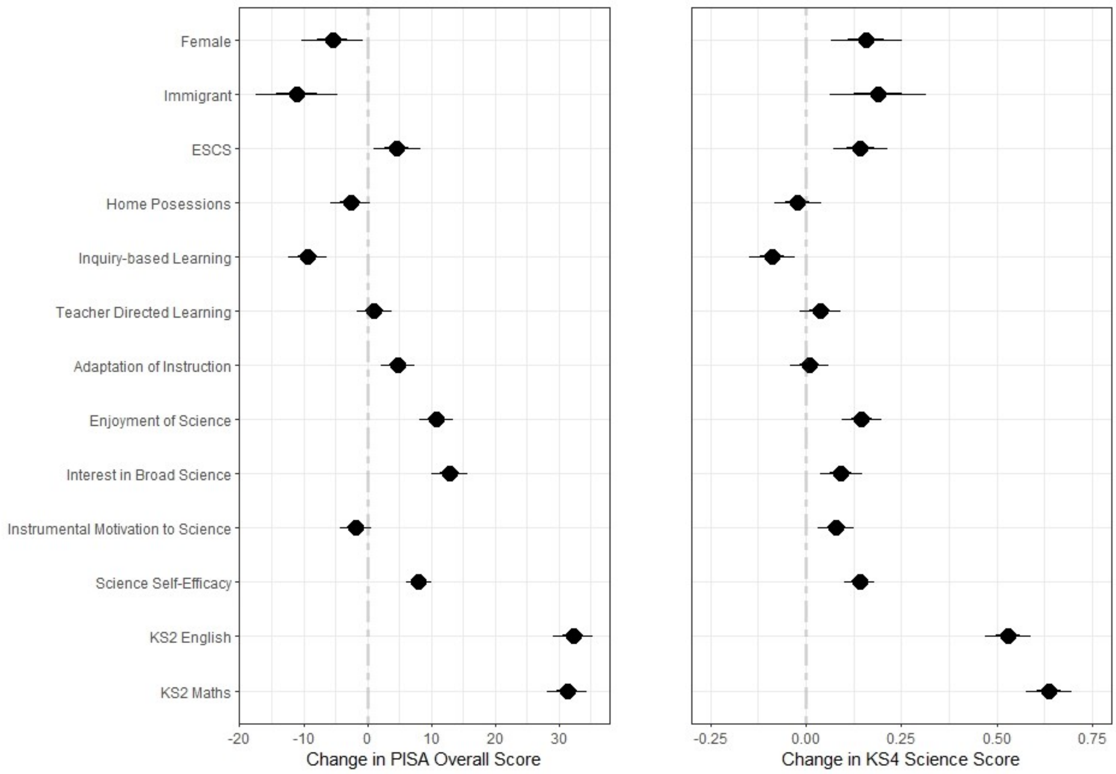
Development of the model

We used the ten plausible values for Science in PISA, included the GCSE pillar point score (KS4), in constructing a multivariate multilevel model. For the PISA overall score 28% of the variance was explained by the school-level and for the KS4 Science score, the figure was 40% before incorporating covariates into the analysis. Initially we added demographic and background covariates such as sex of respondent, first- or second-generation immigrant (treated as a binary indicator), an index of the economic, social and cultural status (ESCS) and a measure of home possessions (HomePos). With further development we incorporated measures of instructional strategies and student reports of enjoyment (JOYSCIE), interest (INTBRSCI), motivation (INSTSCIE) and self-efficacy in science (SCIEEFF). For prior attainment, we used KS scores.

Model Specification

The final development was to fit a multiple outcomes model with four distinct advantages over treating the outcomes independently. Firstly, they allow conclusions to be drawn about the correlations observed between the outcome variables. Secondly, modelling multiple dependent variables simultaneously can increase the statistical power of the model resulting in smaller standard errors at least when the outcomes are sufficiently correlated. Thirdly, it allows for the direct testing on whether the effect of an explanatory variable is larger on one outcome compared to another, and finally, it helps to avoid the impact of the multiple comparisons issue (see Gelman, Hill & Yajima, 2012, p.206-209).

Figure 5: Student-level effects of 'affect' on PISA and KS4



In Figure 5, the student-level effects can directly be compared between the overall PISA score and the KS4 science score outcome. While these measures are not on the same scale, the plots provide an indication of the direction and magnitude of the effects. A one-unit increase in the index of science self-efficacy has a medium to large impact on the overall PISA science score (an average increase of 8.1 points) and a smaller to medium effect on the KS4 science score (an average increase of 0.14 points) after taking account of student demographics, background and home life, style of teaching within classrooms, broad interest and motivation towards science and prior attainment at KS2.

However, in the wider context of the model, a number of other covariates had larger impacts on the PISA Science and KS4 Science scores. In particular, whether the student was a first or second generation immigrant had a negative large impact on the PISA Science score (-11 points), but a positive medium size impact on KS4 Science score (0.19 points) and whether the student perceived the use of inquiry-based learning in science classrooms had a large negative effect on the PISA science score

(-9.3 points) and a smaller negative effect with the KS4 Science score (-0.08 points); whether the student enjoyed science had a large effect on the PISA science score (10.81 points) and a small to medium size effect on the KS4 science score (0.15 points); and whether the student had an interest in broad science had a very large effect on PISA science (12.96 points) and a smaller effect on KS4 Science score. The two covariates that had the most impact were unsurprisingly the KS2 English and Mathematics prior attainment variables which had very large effects on both the PISA score (32.3 and 31.3 points respectively) and the KS4 Science score (0.63 and 0.64 respectively). Correlations between GCSE grades and PISA scores are estimated to be moderately strong (.76 for science, .777 for mathematics) with students who did well on PISA in science, were also those students who scored high grades (A or A*, equivalent to current grades 7-9) on their GCSE examinations, six months later (Carroll & Benton, 2018).

In considering the mediating effects of affective, non-cognitive or dispositional measures, a range of these have been explored here. Instrumental motivation seems to have differential effects on PISA (negative and low) and GCSE (positive and moderate) performance achievement scores.

Our analysis showed that enjoyment of science has a very high positive effect on PISA and a moderate positive effect on GCSE scores. Likewise, self-efficacy has a high positive effect on PISA and a moderate positive effect on GCSE scores and confirms the large-scale analysis of self-beliefs and that self-efficacy (in PISA) was ‘the strongest predictor of students achievement’ (Lee and Stankov, 2018, p. 61). This is a stark finding and reflective of the beliefs that students have about their own ability to learn, master and likely to determine effort and aspiration. This evidence can be used by policy makers, teachers, and schools to develop appropriate interventions to support (especially) low socioeconomic status students.

Examining the impact of enjoyment of science, instrumental motivation, self-efficacy in completing post-16 science

Model Specification

The final model incorporated three demographic indicators – a binary measure of gender; three category immigration status (‘native’ vs. 1st and 2nd generation immigrants); and the index of economic, social, and cultural status which incorporates occupational status of parents, years of schooling of parents, family wealth, home education resources, and cultural possessions within the home. There are a further set of four PISA measures of enjoyment of science, instrumental motivation to science (i.e. whether the student is motivated to study science by desires for future employment and study), interest in broad science topics and self-efficacy towards science. Finally, there is a final set of academic performance measures from Key Stage 4 and from the age 15 PISA study, the Progress Eight score for Mathematics, the Progress Eight score for English and the average GCSE score for Science, and the plausible values the PISA science score.

$$y_i = logit^{-1}(\beta_0 + \beta_1 Female_i + \beta_2 \mathrm{1stGenImmigrant_i} + \beta_3 2ndGenImmigrant_i + \beta_4 ESCS_i + \beta_5 EnjoymentSci_i + \beta_6 InstrumentalMotivation_i + \beta_7 InterestBroadSci_i + \beta_8 SelfEfficacy_i + \beta_9 Progress8Maths_i + \beta_{10} Progress8Eng_i + \beta_{11} KS4AverageSciScore_i + \beta_{12} PVSci_i)$$

Findings

Table 10 presents risk ratios, along with the more familiar odds-ratios for each of the covariates discussed above. Risk ratios should be interpreted in a similar manner to odds ratio in that the incidence of completing a post-16 science qualification (Science A level, for example) should be the same between both the comparison and dummy group where the risk ratio is close to 1. Where the risk ratio is lower than 1, there dummy group has a lower incidence or ‘risk’ of completing the post-16 science qualification, and where the risk ratio is greater than 1 the dummy group have a greater incidence of completing a post-16 science qualification than the comparison group.

Of the three demographic indicators, gender does not have a clear discernible difference as the posterior distribution crosses 1. The mean effect provides weak evidence of a slightly lower incidence of female students completing a post-16 science qualification. However, first generation immigrants are on average 2.5 times (1.80, 3.32) and second-generation immigrants are 2.7 times (2.05, 3.49) more likely to complete a post-16 science qualification than their ‘native’ student peers. Furthermore, those with higher economic, social and cultural statuses i.e. come from backgrounds with less inequality (1 standard deviation higher) are 20% (1.08, 1.34) more likely to complete an AS or A-level in Science.

The four PISA measures of student attitudes to science show some surprising shifts in terms of relative importance compared to previous analyses. Those with higher enjoyment of science (1 standard deviation) were 16% more likely (1.02,1.31), and those with greater interest in broad science, along with greater science self-efficacy were slightly more likely to complete post-16 qualifications in the subject, however the evidence is weaker as the distribution crosses 1 (0.97, 1.26 and 0.95, 1.20 respectively). Those with higher instrumental motivation towards science in PISA are twice as likely to have completed a post-16 science qualification, even though this was weakly and negatively associated with the PISA science score and more positively with the KS4 science score. While these are different outcomes, this was a surprising shift to observe.

Lastly, from the four measures of academic attainment and knowledge, Mathematics and Science attainment were the strongest predictors of completing a science post-16 qualification at AS or A level. Those who scored highly on the Progress Eight in Mathematics were over 1.5 times more likely to complete, and those who score highly in science were 3.3 times more likely to complete AS or A-level science. Higher scores on PISA had a smaller impact with students being 2.1 times more likely to complete.

Table 10: Odds-Ratio and risk ratio estimates and 95% confidence intervals for single-level regression model examining the probability of completing a science AS or A-level by age 18 (PISA 2015 Sample, N=4268).

	Odds-Ratio			Risk Ratios		
Parameter	Estimate	Lower 95% Confidence Interval	Upper 95% Confidence Interval	Estimate	Lower 95% Confidence Interval	Upper 95% Confidence Interval
Female	0.94	0.76	1.15	0.94	0.77	1.14
First-Generation Immigrant	2.67	1.89	3.78	2.45	1.80	3.32
Second-Generation Immigrant	2.99	2.19	4.03	2.70	2.05	3.49
Index of Economic, Social and Cultural Status	1.22	1.09	1.36	1.20	1.08	1.34
Enjoyment of Science	1.17	1.02	1.33	1.16	1.02	1.31
Instrumental Motivation to Science	2.12	1.89	2.39	2.00	1.79	2.23
Interest in Broad Science	1.12	0.97	1.28	1.11	0.97	1.26
Science Self-Efficacy	1.08	0.95	1.22	1.07	0.95	1.20
Pupil's Progress 8 Score for Mathematics	1.59	1.40	1.82	1.54	1.37	1.74
Pupil's Progress 8 Score for English	0.96	0.85	1.08	0.96	0.85	1.07
Pupil’s KS4 Average Science Points Score	3.73	2.96	4.70	3.25	2.65	3.98
PISA Plausible Value for Science	2.26	1.87	2.69	2.12	1.78	2.48

Source: Bespoke English PISA-NPD Dataset provided by the Department for Education

Environmental awareness

Exploring the relationship between students' awareness of climate change and achievement

While PISA does not measure environmental literacy directly, questions focused on students' reported self-awareness of environmental issues enable exploration of associations between measures of scientific literacy, affective dispositions of students and broader factors influencing environmental literacy. 2006 (the last time these items were used prior to 2015), for example, 58% of students reported an awareness of greenhouse gases compared with 73% of students who were aware of the consequences of forest clearing (OECD, 2006). Both in Australia and Turkey, the relationship between students' awareness and scientific knowledge of environmental issues was reported to be linear in Australia (Thomson, De Bortoli & Underwood, 2017; Öztürk, 2018). Given the environmental student activism, we wanted to undertake an exploratory '*analysis of the relationship between achievement, affective measures and awareness (being informed) of the increase of greenhouse gases, as well as the relative influence of home background indices (wealth, cultural possessions, home educational and ICT resources*' (Oliver & Adkins, 2020). We used the World Resources Institute (https://www.wri.org/our-work/topics/climate) and the Climate Change Performance Index (CCPI) (https://www.climate-change-performance-index.org/) to look at historical emissions, local, national and international policies and practices to protect the climate. These publicly available data contributed to our analysis of the PISA data,

As a suite of questions about environmental awareness, students were asked, '*How informed are you about the increase of greenhouse gases in the atmosphere?*' (ST09201TA), each with four options: *I have never heard of this; I have heard about this but I would not be able to explain what it is really about; I know something about this and could explain the general issue; and I am familiar with this and I would be able to explain this well.*

We used a multilevel ordered logistic 'proportional odds' regression model to estimate the individual, school and country level probability of being informed. All ten plausible values in science were added separately before the model was computed. Details of the models and the scaling methodology are publicly available (https://www.sciencedirect.com/science/article/pii/S2214629620302164).

Table 11: Distribution of the outcome variable (environmental awareness) using PISA 2015 data

How informed are you about the increase of greenhouse gases in the atmosphere?	**N (%)**
I have never heard of this	51090 (9.8%)
I have heard about this but I would not be able to explain what it is really about	127728 (24.6%)
I know something about this and could explain the general issue	182110 (35.1%)
I am familiar with this and I would be able to explain this well	107172 (20.6%)
Missing	51234 (9.9%)
Total	519334 (100%)

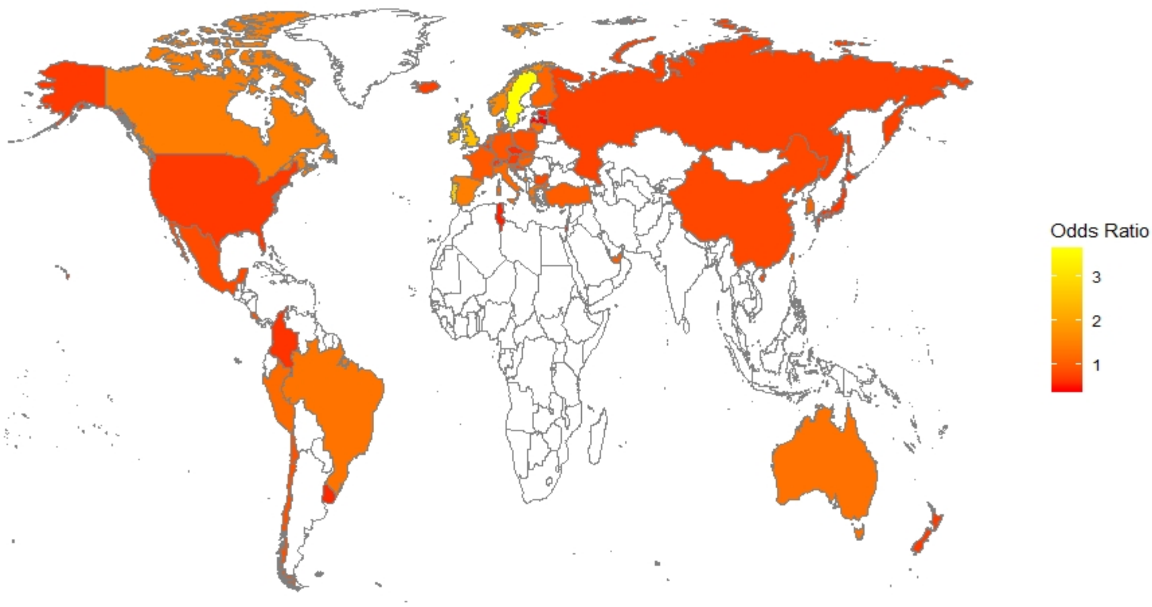
A baseline measure shows that nearly 56% of students know '*something about this'* or '*able to explain it well*'. Given the warnings about climate change, it is surprising that so many students do not feel well informed about the increase of greenhouse gases. The regression model shows that the largest predictor for individuals of being well-informed is the PISA score. Other factors are gender, enjoyment of science, interest in broad science topics and cultural possessions. We wondered if this was the case for individual, whether the same pattern could be observed at the country level. Do the high-achieving countries in PISA also have students who are well-informed? Figure 6 shows this is not so clear cut.

Parameter	Posterior mean (SD)	Posterior 95% credible intervals	Odds-ratio 95% credible intervals	Probability scale 95% credible interval
Sex of respondent	−0.14 (0.03)	−0.20, -0.08	0.82, 0.92	−0.05, −0.02
Immigrant (First generation)	0.11 (0.02)	0.07, 0.15	1.07, 1.16	0.02, 0.04
Immigrant (Second generation)	0.01 (0.02)	−0.02, 0.05	0.98, 1.05	−0.01, 0.01
Parental Education	0.01 (0.00)	0.01, 0.01	1.01, 1.01	0.02, 0.02
Highest Occupational Status of Parents	0.04 (0.01)	0.03, 0.05	1.03, 1.05	0.01, 0.01
Cultural Possessions	0.14 (0.01)	0.13, 0.15	1.14, 1.17	0.03, 0.04
Home education resources	0.08 (0.01)	0.07, 0.09	1.07, 1.09	0.02, 0.02
Wealth	0.03 (0.01)	0.01, 0.05	1.01, 1.05	0.00, 0.01
ICT resources	−0.02 (0.01)	−0.04, 0.00	0.96, 1.00	−0.01, 0.00
Enjoyment of science	0.32 (0.01)	0.31, 0.33	1.37, 1.40	0.08, 0.08
Interest in broad science	0.32 (0.01)	0.31, 0.33	1.36, 1.39	0.08, 0.08
Instrumental motivation to science	0.03 (0.00)	0.02, 0.04	1.02, 1.04	0.00, 0.01
PISA Score	1.69 (0.05)	1.59, 1.76	4.91, 5.96	0.33, 0.36
CO_2 emissions per capita	−0.01 (0.01)	−0.03, 0.01	0.98, 1.01	−0.01, 0.00
Sex*PISA score	−0.16 (0.02)	−0.20, −0.11	0.81, 0.90	−0.07, −0.05
Cutpoints				

Parameter	Posterior mean (SD)	Posterior 95% credible intervals	Odds-ratio 95% credible intervals	Probability scale 95% credible interval
(I have never heard of this) (I have heard about this, but I would not be able to explain what it is really about)	−2.73 (0.06)	−2.86, −2.62		
(I have heard about this, but I would not be able to explain what it is really about) (I know something about this and could explain the general issue)	−0.57 (0.06)	−0.70, −0.46		
(I know something about this and could explain the general issue) (I am familiar with this and I would be able to explain this well)	1.88 (0.06)	1.75, 2.00		

Figure 6: The probability of perceiving being informed about the increase of greenhouse gases: country level intercept variation

The probability of perceiving being informed about the increase of greenhouse gases: country level intercept variation.



The positive effects of enjoyment and interest are to be noted as these are likely to be reflective of the school, environment, and the curriculum. Students in Sweden, for example, and well informed, perhaps reflecting the wider societal discourse, policies and enacted practices to mitigate climate changes and an education where environmental responsibility is embedded from the early years. Portugal, too, also leads Europe in this regard, where students are well-informed about climate change. New Zealand on the other hand, is a top-performing PISA country, a medium-ranked CCPI country yet students there are among the least-informed about the role of greenhouse gases in climate change. When we looked at the NZ school curriculum, we could not find any curriculum content relating to climate change until the last two years of high schools, although there are a number of environmental emergencies that teachers and student need to cope with in their everyday life – from volcanoes and earthquakes to tsunami. Students in the USA feel less informed than their peers in Canada, other American countries and Europe. The political discourse around greenhouse gases, role in international commitments to mitigate climate change contribute to the US being among ‘the worst-performing countries’ (Burck, 2019) in regard to national and international policies. The lack of environmental education leaves students wanting.

Conclusion

This report summarises the analysis of the PISA 2015 data. These are drawn from 15-year olds in schools, responses to science questions form the achievement 'score' for scientific literacy and students' responses about the frequency of their classroom experiences form PISA-constructed compound variables or indices of instructional approaches. Our focus was exploring the different instructional approaches and then specifically to explore the disaggregated variable of 'inquiry'.

- In all six Anglophone countries, our analysis shows that students who reported experiencing high frequencies of inquiry strategies in their classrooms consistently evidenced lower levels of scientific literacy across the six countries. There is a strong and negative association between inquiry-based teaching and scientific literacy.
- Although the measure of inquiry-based teaching within our dataset is based upon information reported by students, there may well be examples where inquiry-based teaching results in very high levels of student learning: we do not observe that using these PISA data. We cannot comment on the quality of the classroom experiences but the consistent patterning of responses across six (culturally similar) countries, suggests that the associations between achievement and instructional approaches are trustworthy.
- Conversely, we found a strongly positive association between the frequency of teacher-directed and adaptive teaching strategies and students' scientific literacy.
- Doing practical work *every lesson* or *very rarely* is unlikely to support the development of students' scientific literacy.
- While enjoyment of science is a predictor for GCSE science, instrumental motivation seems to have a greater predictive and positive association on A level choices.
- Enjoyment of science has a very high positive effect on PISA and a moderate positive effect on GCSE scores. Instrumental motivation seems to have a greater predictive and positive association on A level choices

- Self-efficacy has a high positive effect on PISA and a moderate positive effect on GCSE scores and confirms the large-scale analysis of self-beliefs and that self-efficacy (in PISA) was ‘the strongest predictor of students achievement’ (Lee and Stankov, 2018, p. 61).

- Discourse around greenhouse gases, commitments to mitigate climate change in regard to local, national and international policies are important for school students. The lack of environmental education leaves some students wanting.

PISA data are drawn from 15-year olds in schools. The OECD recognises that not all young people are in schools, so any analysis of these data needs to be understood with this caveat in mind.

Implications and Recommendations for Policy and Practice

- Some aspects of inquiry-based teaching warrant greater support in schools: the cognitive, rather than procedural and behavioural, or the ‘doing’ of science.

- Consistent with the predictions of cognitive load theory (see Kirschner et al., 2006) we find that moderate levels of highly guided inquiry-based teaching have a stronger ($d \approx 0.2$) relationship with student attainment on high-stakes GCSE.

- When science teachers use inquiry-based teaching, it should be carefully guided, well-planned and scaffolded as this leads to positive cognitive and affective outcomes (Aditomo et al., 2019).

- There is a positive association between inquiry-based teaching and ‘positive dispositions towards science’ (Cairns & Areepattamannil, 2019), such as enjoyment and interest in science (McConney et al., 2104). These are important findings to share with teachers and science educators in developing proficiency in using inquiry-based teaching.

- The role of self-efficacy as the largest predictor of achievement, is an important finding and reflective of the beliefs that students have about their own ability to learn, master and likely to determine effort and aspiration. This evidence can be used by teachers and schools to develop appropriate interventions to support (especially) low socioeconomic status students. Importantly for policy makers, and those concerned to improve the quality of science education, attention needs to be given to how self-efficacy can be nurtured, developed and sustained in students.

- Environmental responsibility needs to be embedded into the curriculum from the early years.

- Science is currently a ‘poor relation’ in the curriculum in many primary schools (Ofsted, 2021). Further research needs to explore the relative decline in performances in TIMSS, and of primary students in biennial tests and the extent of science experiences in primary schools in England. This will require both exploring teachers’ and students’ experiences using TIMSS and observational classroom data.

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Appendix A: instructional approaches

Survey questions were used to create several composite variables, including indices of inquiry-based instruction (IBTEACH), adaptive instruction (ADINST), and teacher-directed, instruction (TDTEACH). To illustrate how individual items PISA constructed a composite variable, students' responses to survey items about the frequency with which they experienced specific activities. Each of the individual items comprising these indices asked students to indicate using a four-point scale ('in all lessons'; 'in most lessons'; 'in some lessons'; 'never or hardly ever'), the frequency with which they experience various learning and teaching activities or strategies. For all indices, higher values indicate that the activities happened more frequently in science lessons (OECD 2016b).

Adaptive instruction (ADINST)

Three items were included:

1. *The teacher adapts the lesson to my class's needs and knowledge*;
2. *The teacher provides individual help when a student has difficulties understanding a topic or task*;
3. *The teacher changes the structure of the lesson on a topic that most students find difficult to understand*.

Inquiry-based instruction (IBTEACH)

Nine items were included in this composite variable:

1. *Students are given opportunities to explain their ideas*;
2. *Student spend time in the laboratory doing practical experiments*;
3. *Student are required to argue about science questions*;
4. *Student are asked to draw conclusions from an experiment they have conducted*; *the teacher explains how a science idea can be applied to different phenomena*;
5. *Student are allowed to design their own experiments*;
6. *There is a class debate about investigations*;
7. *The teacher clearly explains the relevance of science concepts*;
8. *Student are asked to do an investigation to test ideas*

Teacher-directed instruction (TDTEACH)

Four items were included:

4. *The teacher explains scientific ideas;*
5. *A whole class discussion takes place with the teacher;*
6. *The teacher discusses our questions*;
7. *The teacher demonstrates an idea*.

Each of the individual items asked students to indicate using a four-point scale ('in all lessons'; 'in most lessons'; 'in some lessons'; 'never or hardly ever'), the frequency with which they experience various learning and teaching activities or strategies. For all indices, higher values indicate that the activities happened more frequently in science lessons (OECD 2016b).

Combined student responses provide an index of each instructional approach, where higher values indicate more frequent use of this approach. We used the three indices representing distinct teaching/learning approaches (ADINST, IBTEACH, TDTEACH), categorical variables such as country, and PISA's composite measure of student socioeconomic status (ESCS), as a covariate (OECD, 2016a, 2016b).

Appendix B: non-cognitive, affective variables

Enjoyment of science (JOYSCIE) (ST094- 5 items)

Students respond on a four-point Likert scale with the categories ‘strongly agree’, ‘agree’, ‘disagree’, and ‘strongly disagree’. The derived variable JOYSCIE was scaled using the IRT scaling model enabling a trend comparison between PISA 2006 and PISA 2015 at the country level.

- I generally have fun when I am learning <broad science> topics
- I like reading about <broad science>.
- I am happy working on <broad science> topics.
- I enjoy acquiring new knowledge in <broad science>
- I am interested in learning about <broad science

Interest in broad science (INTBRSCI – 5 items) new in 2015

- To what extent are you interested in the following topics in broad science
- Biosphere (e.g. ecosystem services, sustainability)
- Motion and forces (e.g. velocity, friction, magnetic and gravitational forces)
- Energy and its transformation (e.g. conservation, chemical reactions)
- The Universe and its history
- How science can help us prevent disease

Self-efficacy (SCIEFF) ST129 – 9 items used in 2006 and 2015

- How easy would it be for you to perform the following tasks on your own?
- Recognise the science question that underlies a newspaper report on a health issue.
- Explain why earthquakes occur more frequently in some areas than in others.
- Describe the role of antibiotics in the treatment of disease.
- Identify the science question associated with the disposal of garbage.
- Predict how changes to an environment will affect the survival of certain species.
- Interpret the scientific information provided on the labelling of food items.

- Discuss how new evidence can lead you to change your understanding about the possibility of life on Mars.
- Identify the better of two explanations for the formation of acid rain.

Instrumental motivation (INSTSCIE) – 4 items)

- Making an effort in my <school science> subject(s) is worth it because this will help me in the work I want to do later on.
- What I learn in my <school science> subject(s) is important for me because I need this for what I want to do later on.
- Studying my <school science> subject(s) is worthwhile for me because what I learn will improve my career prospects.
- Many things I learn in my <school science> subject(s) will help me to get a job.