UNIVERSITY OF YORK
SCIENCE EDUCATION GROUP

Practical, open-ended and extended investigative projects in science

Report to The Gatsby Charitable Foundation

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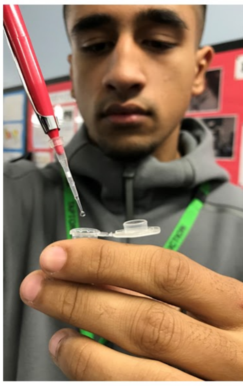
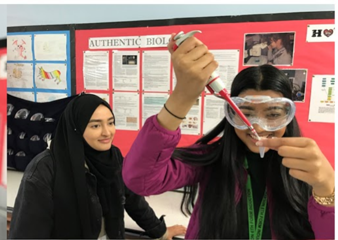
List of abbreviations

A Level	Advanced Level
ALPS	Advanced Level Performance System
AQA	Assessment and Qualifications Alliance
AS	Advanced Supplementary
ASE	Association for Science Education
BTEC	Business and Technology Education Council
CPAC	Common Practical Assessment Criteria
CREST	Creativity in Science and Technology
EPQ	Extended Project Qualification
GCSE	General Certificate of Secondary Education
IB	International Baccalaureate
IRIS	Institute for Research in Schools
MOOC	Massive Open Online Course
NQT	Newly Qualified Teacher
Ofsted	Office for Standards in Education
OCR	Oxford Cambridge and RSA
PGCE	Postgraduate Certificate of Education
PTA	Parent Teacher Association
RSB	Royal Society of Biology
RSC	Royal Society of Chemistry
SAC	Salters Advanced Chemistry
SAPS	Science and Plants for Schools
SHAP	Salters Horners Advanced Physics
STEM	Science, Technology, Engineering,
UCAS	Universities and Colleges Admissions Service





Executive summary

The purpose of this study is to report on teachers' use of open-ended investigative work post-16. The Gatsby Good Practical science report identifies opportunities to carry out open-ended work as one of their ten benchmarks for good practical science, yet there is currently no requirement for students in England to have access to the opportunity to carry out such work, which means that such work is often pushed to the margins. This study aimed to find out why and how teachers use open-ended investigative work with students in order to identify ways in which it can be possible in schools in England.

Short questionnaires and extended semi-structured interviews were used to collect data. A total of seventeen teachers responded to the questionnaire and twelve teachers were interviewed. All teachers interviewed had been teaching for longer than 5 years and worked in schools or colleges rated 'good' or 'outstanding' by Ofsted. Teachers were asked about enablers and barriers to the work, and the ways in which they negotiated these. Findings are presented as case studies in order to be relatable to other teachers. The case studies provide information about the project, who participates, intended and perceived learning outcomes, the role of the teacher, school support and advice for other teachers.

Open-ended investigative projects were characterised according to their degree of open-ness, i.e. what was provided to students from the following dimensions: problem and background, procedures, design or methodology, analysis and conclusions. Projects in which teachers provided all dimensions (confirmatory projects) were excluded from the report. Most teachers in the sample provided the theoretical context, with students able to make decisions about research design, analysis and conclusions. Ongoing or ad-hoc support was a feature of many projects, and whilst most projects were not assessed, they were often used to meet the Common Practical Assessment Criteria (CPAC) or made to 'count' in other ways. Most projects were carried out during class time, sometimes including collapsed days in the summer term. Five big themes were identified in terms of what teachers wanted students to learn: 'real' science, the state of the field, research design, iteration and data handling.

Enablers of open-ended investigative work in the curriculum include teacher experience and autonomy, technical support, support from senior leadership, laboratory space and equipment budget, examination specifications, and external support and recognition. Challenges in providing access for students to open-ended investigative projects include access to literature, laboratory space, expertise and equipment, numbers of students and technicians in relation to number of teachers. Teachers in the sample found ways to negotiate or to overcome these barriers, which are likely to be useful to teachers considering offering open-ended project work in the curriculum. Time remains an intractable issue for all teachers in the sample.

This report includes data only from teachers who were dedicated to providing open-ended investigative projects to their students; there may be additional barriers to doing this that affect the wider science teacher population. All of the teachers are based in schools or colleges rated outstanding or good by Ofsted, and many teach within their specialism. The conditions in other institutions may contribute to barriers to open-ended investigative projects and care must be taken to avoid widening educational inequalities in terms of access to open-ended investigative projects.

Whilst open-ended investigative projects can be integrated into the post-16 curriculum, where this is not a requirement of the specification, it tends to rely on work beyond timetabled hours from teachers. Several teachers in this sample found ways of making project work 'count', for example by relating it to the CPAC, linking to award schemes, offering as an alternative to other scheduled teaching and learning activities and encouraging students to write about their experiences on UCAS applications. Some teachers in this study believed that open-ended investigative work had a positive impact on attainment post-16, and there may be value in researching this claim because if evidence did support the claim, more teachers may be convinced to introduce project work, even if not required by specifications.

To increase the uptake of open-ended investigative project work at post-16, we recommend a range of actions. Exemplars of 'making open-ended investigative projects count,' could be made available to teachers, with attention to ways of minimising risk (particularly in chemistry projects), and teacher and technician time for project work through workload models and buy-out could be valued. Research investigating claims about the impact of open-ended investigative work on attainment would build a more convincing case to teachers who are currently reluctant to introduce open-ended project work. Assessment is an important driver for classroom practice, and a way to ensure that this happens is to change policy to require open-ended investigative work in post-16 examination specifications. However, where open-ended investigative work is to be included in specifications, care must be taken to avoid assessment methods that result in a formulaic approach to investigative project work.

Introduction

Open-ended and extended investigative projects have been identified as a benchmark for good practical science (Gatsby, 2017) yet recent changes introduced to the Advanced Level (A Level) specifications mean that there is no longer a requirement for most post-16 students in England to undertake open-ended investigative work. A recent study found few teachers to be undertaking open-ended investigative work (Cramman et al., 2019). The purpose of this study, drawing on questionnaire responses and semi-structured interviews, is to report on the types of open-ended investigative work undertaken, why teachers do it, how it is organised, and what teachers perceive the opportunities and challenges of such work to be. In contrast to the recent rapid evidence review on Independent Research Projects published by the Wellcome Trust (Bennett, Dunlop, Knox, Reiss & Torrance Jenkins, 2016) this report focuses on open-ended investigative projects (of which research projects are one type), and on what teachers do to make these possible post-16.

Investigations are defined as tasks in which students design an experiment to test a given question, carry it out and interpret the results, all within a fixed time period (Gatsby, 2017). In investigative work, students cannot immediately see an answer or recall a routine method for finding it (Gott and Duggan, 1995 p.14). That is to say, that whilst procedures and results might be known to science, they are not familiar to the student doing the investigation, and there is no pre-determined outcome (Gatsby, 2017). Investigations can be open to different degrees, and in this report, projects that are open in at least one of the following six dimensions identified by Buck, Bretz and Towns (2008) are considered open-ended: the problem/question, theory/background, procedures/design, analysis of results, communication of results and conclusions. Confirmation projects in which the problem/question, theory and background, procedures and design, analysis, interpretation and conclusions are provided for the students are excluded from this study.

There is evidence to suggest that open-ended investigations support students to learn science ideas and to develop a range of skills as well as improve attitudes towards science (see for example Bennett et al., 2018). This report presents a series of case studies from 12 teachers working in England. Each carries out open-ended investigative projects, corresponding to the *Good Practical Science* benchmark, with post-16 students in England. From the set of case studies, intended learning outcomes have been extracted along with understanding how teachers have negotiated the barriers to participation in such work. The case studies provide relatable examples of how teachers can provide opportunities for open-ended investigations in a demanding post-16 environment and present ways in which teachers have overcome barriers to offering open-ended investigative project work. The questions that the report answers are as follows:

- How do science teacher approaches to practical, open-ended and extended investigative projects vary?
- What do teachers want students to learn by carrying out practical, open-ended and extended investigative projects in science, and how do they bring this about?
- How do teachers see their role in supporting students to carry out practical, open-ended and extended investigative projects in science?
- What enables successful practical, open-ended and extended investigative project work in schools or colleges, and what barriers exist?

Methods

Ethical approval to conduct the study was obtained from the relevant departmental ethics committee; and voluntary informed consent obtained from participating teachers.

Invitations to take part were distributed via professional networks of teachers in the UK, inviting responses from any teachers who carried out open-ended investigative work at post-16. A questionnaire and interview were used to collect data. The questionnaire was circulated electronically. This consisted of open and closed questions (see appendix 1). The closed response items were based on Buck et al. (2008) and were used to characterise projects (Table 1). Note the definition of authentic, which refers to the characterisation of inquiry and not 'authentic science' in which students participate in cutting-edge scientific research projects. The open response items asked teachers to identify their intended learning outcomes and what students need to know in order to do successful open-ended investigative projects. A total of 17 questionnaires were returned.

	Provided?	Provided?	Provided?	Provided?	Provided?
Problem/Question	yes	yes	yes	yes	no
Theory/Background	yes	yes	yes	yes	no
Procedures/Design	yes	yes	yes	no	no
Analysis of results	yes	yes	no	no	no
Communication of results	yes	no	no	no	no
Conclusion	yes	no	no	no	no
Characterisation	**Confirmation**	**Structured**	**Guided**	**Open**	**Authentic**

Table 1: Characterising open-ended investigative work

Questionnaire responses were screened and only those projects that were structured, guided, open or authentic (n=15) were included in further analysis. These were projects in which at least one of the following were *not* provided to students: the problem or question, theory and background, procedures and design, analysis, interpretation and conclusions. All teachers doing confirmation projects were excluded from the sample prior to interviews. Questionnaire responses were then analysed independently by three researchers to identify central concepts in relation to learning through open-ended investigative projects. This resulted in the identification of the central concepts, or key themes, which captured the essence of the questionnaire responses. Following reflexive discussion, five key concepts were identified. These informed the design of the interview guide.

Selection criteria were then used to invite teachers for interview. These were teachers who (i) offered and carried out open-ended investigative work (structured, guided, open or authentic) with post-16 students and (ii) worked in state (non-fee paying) schools or colleges. A total of 12 teachers agreed to take part in interviews. The interview guide is found in appendix 2. Teachers were asked about their project, how it was organised, how they supported students to learn each central concept identified from the interviews, and how they dealt with various barriers to carrying out open-ended investigative work. The interview guide drew on questions used to reveal teachers' pedagogical content knowledge (Loughran, Berry & Mulhall, (2012) in relation to the key concepts identified from the questionnaires. Interviews were recorded, transcribed and then analysed to identify (i) how science teacher approaches to practical, open-ended and extended investigative projects vary; (ii) what teachers want students to learn by carrying out open-ended investigative projects in science, and how they bring this about; (iii) how teachers see their role in supporting students to carry out open-ended investigative projects in science; and (iv) what enables successful project work in schools or colleges, and what barriers exist. The transcripts were used to create case studies for each teacher.

The following section identifies the characteristics of the teachers who were interviewed and the schools and colleges in which they teach.

The teachers

A total of 12 teachers were interviewed, four female and eight male. The teachers worked across the science disciplines (Figure 1) and taught different post-16 programmes, with A Levels being the most common (Figure 2). All teachers in the sample had been in the profession for longer than 5 years, and half had been teaching for over 15 years.

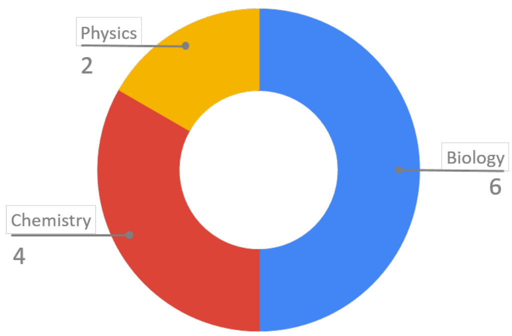


Figure 1: Science specialisms

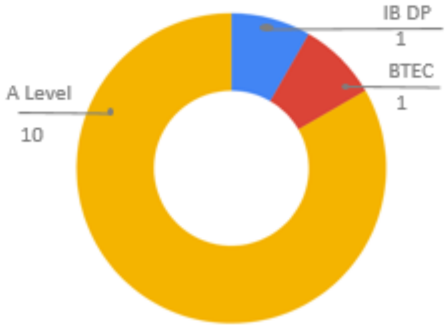


Figure 2: Post-16 programme taught

All teachers worked in schools and colleges in the state sector. Three teachers worked in post-16 colleges and 9 teachers worked in 11-18 schools. Of the schools, three operated academic selection policies for some or all entrants. All schools and colleges had a good or outstanding Ofsted rating, with the majority (n=7) rated outstanding.

Teachers were working in schools and colleges located across England (Dorset, Kent, London, Norfolk and Yorkshire) in a range of neighbourhood types, from rural town fringes to major urban conurbations. The majority (n=10) were located in the least deprived neighbourhoods in England (i.e. above the fifth decile) and only one was located in a neighbourhood in the most deprived decile.

Teachers' reasons for doing open-ended projects fell broadly into two main categories, with some overlap: teachers involving students in pursuing teachers' own scientific interests, and teachers doing projects for their educational value, either as a legacy from specifications that previously required open-ended investigations[1] or because they met current specification requirements. Although not universal amongst the sample, there were clear tendencies for teachers in the first category to provide opportunities for students to learn about the current state of the field, and to offer freedom within a teacher-defined field. For one, "it's almost been a necessity for me to do it and it's kept me in the profession possibly because it's opened my mind and it allows me to do science in a different way." Similarly, there were tendencies amongst teachers offering projects for their educational value to allow students to decide on the direction of the project, constrained by technique or resources. Teachers in both groups saw the potential for open-ended investigative work to meet the Common Practical Assessment Criteria (CPAC).

[1] The specifications quoted were Salters Advanced Chemistry, SAC (OCR B) and Salters Horners Advanced Physics (Edexcel)

Findings

How do science teacher approaches vary?

The findings are presented in three parts. In the first, the characteristics of open-ended investigative projects for the case study teachers are described and the key learning outcomes that teachers desired through open-ended investigative projects are identified, along with enablers identified by teachers in the sample. In the second part, teacher case studies are presented. These focus on a single project; many teachers had been involved with, or were involved with, multiple projects with students in different year groups. Finally, we present a synthesis of the constraints on teachers' capabilities to offer open-ended investigative work, and how these were negotiated.

How is open-ended investigative work characterised?

The projects described were unique to each teacher in the sample, and these were open to varying degrees. Figure 3 summarises how the projects can be characterised using Buck, Bretz and Towns' (2008) rubric (Table 1). Most teachers in the sample (n=5) were offering 'open inquiry' projects, in which the problem and background are provided, but the procedures/design/methodology were for the student to design, as were the analysis and conclusions. Fewer (n=4) offered students the opportunity to do 'authentic inquiry' in which the problem, procedures/design, analysis, communication, and conclusions were all for the student to design: for some this was the specification requirement. A minority (n=3) offered structured or guided projects in which students were provided with the problem, procedures, and (in the case of structured projects) analysis by which students can discover relationships or reach conclusions unknown to them. 'Authentic inquiry' projects were typically constrained by availability of equipment and resources as students were only able to pursue their own interests when they had the means by which to collect and analyse data. 'Open inquiry' projects were typically constrained by teachers' interests as in these projects the teachers present students with the problem or background information.

Teachers in the sample who offered open, guided or structured investigative projects did so for a range of reasons, including managing staff time in planning and resourcing the projects, scaffolding students' learning by constraining choice and providing a satisfying experience for students where they would collect sufficient data to analyse meaningfully in the time available.

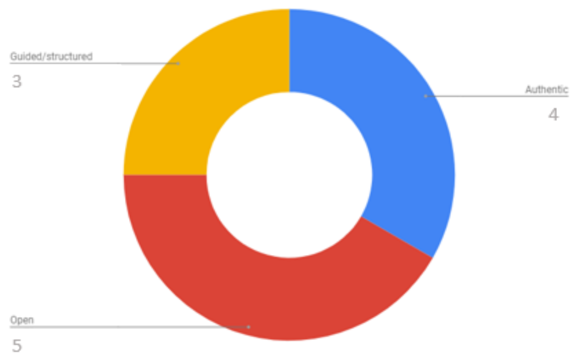


Figure 3: Characterisation of projects in the sample

All teachers in the sample valued open-ended investigative projects, even those who were obliged to carry them out as part of their specification (for example, the IB Diploma Programme and BTEC).

How is open-ended investigative work organised?

The organisation of open-ended investigative work varied across teachers in the sample. Some teachers were working in schools or colleges where open-ended investigative work took place across the sciences or in individual subject (i.e. Biology, Chemistry or Physics) sections. Others were the only teacher carrying out open-ended investigative work at post-16, or one of a small number of science teachers in the school. Just over one-third worked in partnership with external scientists from the inception of the project whereas one-third worked entirely independently and just under one-third sought *ad hoc* support from outside the school (Figure 4).

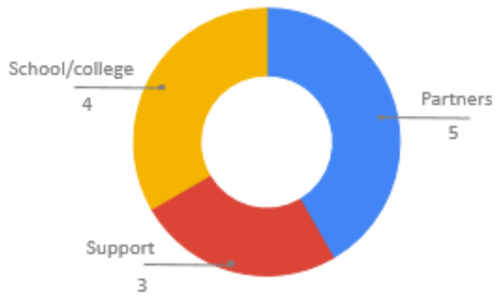


Figure 4: Model of organisation with partners

Teachers offered open-ended project work to post-16 students in a range of ways. In three cases, project work was a requirement because students were assessed (Figure 5) for the IB Diploma Programme, the BTEC and for a CREST Award (the latter offered as a timetabled subject in a school where students are required to do either four A Levels or three A Levels and another timetabled academic activity). In addition, some teachers used open-ended investigative projects to support students to meet the CPAC.

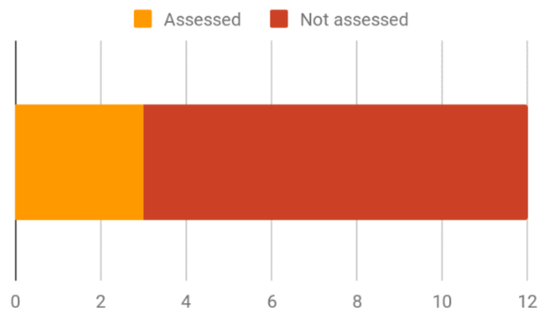


Figure 5: Assessment of projects

Most projects in the sample were offered in timetabled class time, with only three exclusively using extracurricular time (Figure 6). These three projects were *offered* to all post-16 students, but required both teachers and students to give up free time at lunch or after school or college. Teachers used time outside timetabled lessons when the project required scarce equipment, equipment that required specialist training to use, where external collaborators were involved, or they wanted to test an approach to later use in lessons.

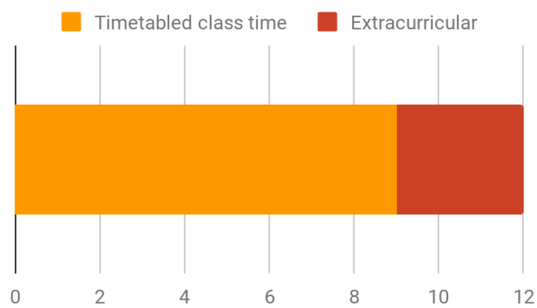


Figure 6: Scheduling of projects

Some teachers required students to carry out an open-ended investigative project either because it was part of the specification or their timetabled requirements (Figure 7) or because it was done in timetabled lessons, either for all or for a subset of students in the lesson. Even projects that students were required to do often included work that took place outside usual scheduled lessons, e.g. as 'collapsed' days in the summer term.

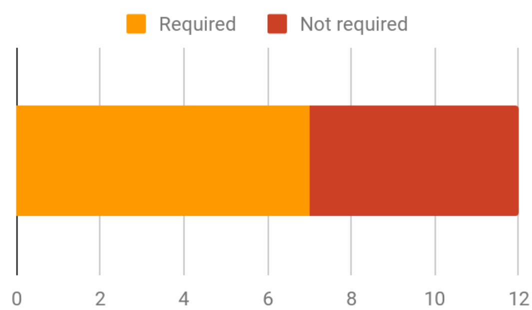


Figure 7: Optionality of projects

Learning through open-ended investigative projects

In order to focus interviews on the how, why and what of learning, questionnaire responses were analysed to identify a small number of 'big themes' associated with learning through open-ended investigative projects. These are presented in Table 2, along with the contributing description found in teachers' questionnaire responses.

Central learning outcome or 'big idea'	**Description**
'Real' science	This idea refers to the sense that open-ended investigative projects give students the chance to find out about 'real' science, or work more similar to the things scientists do.
Data handling	This idea refers to several aspects of data handling that are important for students to learn about including evaluation of data and claims by others, decisions about data collection (including how decisions are made about the suitability and adequacy of data), data analysis, interpretation and data presentation (for example statistics and graphs).
Research design	This refers to the decisions students make about the methods they will use to carry out a project that answers a research question. This includes decisions about experimental design, the methods of data collection and analysis, equipment, safety and ethics.
State of the field	This idea relates to learning about how knowledge is created in the discipline, including how to search, and review the research literature and understand how their work contributes to understanding the state of the field.
Iteration	This refers to the repetitive and recursive (rather than linear) process linking data collection and analysis during which students might notice unexpected results, test procedures, gain experience of trial and error, or make amendments to their methods.

Table 2: 'Big themes' that teachers intend students to learn through open-ended investigative projects.

In addition to identifying central learning outcomes specific to investigative work, some teachers used project work as a context in which students could apply previously learnt subject knowledge, practical techniques or mathematics and statistics. There was an appetite for thinking about how to build progression in understanding these 'big themes' but teachers felt that there was little opportunity to carry out investigative work at Key Stage 4.

Other perceived outcomes of open-ended investigations for students reported by teachers included resilience, confidence, motivation, organisation, independence, presentation and communication skills, time and project management, leadership, problem-solving, improved attainment, and awareness of careers in science.

Enablers of open-ended investigative projects in the curriculum

A range of enablers of open-ended project work were identified by teachers during interviews, and these are presented below in spheres of influence, starting with the teacher, working out to the science department, school senior leadership to local scientists and finally national policy.

Science teachers' prior experiences were an important enabler of open-ended investigative work. Some discussed their own undergraduate, postgraduate or industrial research experience, and others drew on their experience of teaching open-ended investigative work through previous versions of specifications, most notably OCR Salters' A Level. As well as experience, freedom to decide what to teach and when was identified as enabling teachers to plan and conduct open-ended investigative work with students.

In the science department, heads of department enabled open-ended investigative work by ensuring timetabling, room allocation and staffing for this work. The availability of skilled technicians was also important in supporting teachers with finding, testing and refining procedures, carrying out and sharing risk assessments, and maintaining equipment, consumables and living organisms. In some cases, technicians played a role in training students in procedures.

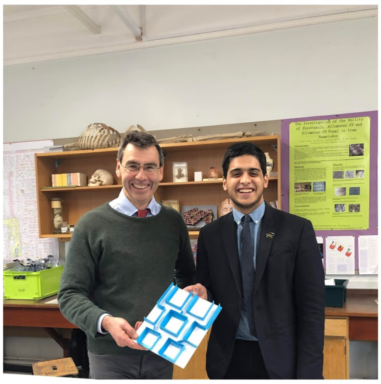
Beyond the science department, school leaders enabled project work by selecting a post-16 curriculum that values open-ended investigative work and allocating staff time and space to this, including time for planning. Project work was also enabled where school and college libraries were well-resourced and staffed by librarians who could help with literature search strategies. They also enabled project work where policies supported teachers to offer open-ended projects within or beyond the curriculum, and where single-discipline teaching was prioritised. Delegation of decision-making to departments over budget spend and when teaching 'year 13 content' started was also important in enabling science teachers to carry out open-ended investigative work.

The scientific community enabled project work in schools. This came in the form of access to scientific support, for example in answering teachers' questions, teacher professional development, direct work with students and/or teachers to plan and carry out project work, and the availability of hands-on support e.g. in chemical analysis. Grant funding (particularly when it involved teacher buy-out) also enabled teachers to carry out investigative work.

Finally, the assessment policy context had a role to play in enabling open-ended investigative work. Teachers in the sample were concerned that previous iterations of investigative work in GCSE specifications had resulted in a formulaic approach. The absence of investigative work in specifications was also seen as problematic. Where project work was well integrated into timetabled lessons at post-16, teachers were following specifications that required this (the IB Diploma Programme; BTEC), were using alternative award schemes (CREST) or were using open-ended investigations to demonstrate that a student had met the CPAC. Teachers felt that the CPAC offered the opportunity for creativity in the assessment of practical work and multiple opportunities allowed teachers to plan for progression, moving from very structured practical work to open-ended investigative work.

Case studies

The following section presents case studies from the twelve teachers to demonstrate the range of open-ended projects undertaken by teachers.



BTEC Applied Science investigative project

Alison Ackroyd
BTEC Science tutor, specialism Biological Sciences
MidKent College

Project description

Part of the BTEC Applied Science curriculum. All students choose topics from the three main science subjects, within reason, depending on staff availability for supervision. These might involve applying previously learnt procedures such as titrations and aseptic techniques, or using specialist equipment in college, for example using HPLC (high performance liquid chromatography) to analyse caffeine in drinks. The projects are internally assessed and then externally verified. Project work is carried out in curriculum time, but students can use a free lab if a member of staff is available to supervise.

Who participates?

All BTEC Applied Science Level 3 students, in their second year, as part of their statutory assignments.

Intended learning outcomes

Alison wants students to learn to synthesise theory, to plan projects, to be resilient and develop employability skills as well as gaining a broader perspective on science.

Teacher's role in supporting the project

Alison sees her role primarily as timekeeper and health and safety manager. She teaches about academic integrity (referencing and plagiarism) in preparation for project work. She also provides checks and balances to ensure students remain focused on their question.

Advice for teachers interested in doing open-ended investigative projects

Look at what the professional societies provide. Also investigate MOOCs, science learning partnerships, Twitter, STEM learning and TeachMeets.

About the college

MidKent College is one of the largest further education and training providers in the South East for post-16 students, offering BTEC Science. Teachers generally teach within their specialism.

Perceived outcomes for students

Confidence in the lab, which Alison sees as excellent preparation for further work and study, as well as improved organisation, resourcefulness and communication.

School support

The biology technician plays an important role in finding, testing and adapting appropriate protocols to ensure they work. Alison has a supportive senior leadership team in that they have dedicated time (in the timetable), equipment and human resources to the development of new topic areas. The projects also have dedicated lab space with a nearby technician and prep room.

"Technicians I think are key, if you don't know how to do something, often there will be somebody there that has done it all before, and has looked to see what you have got in house"

CPAC & CREST Awards

Aba Adebanjo, Chemistry teacher, CREST Award lead, Careers Coordinator (STEM)
Westminster City School

Project description
Aba provides students with opportunities to do open-ended investigative work throughout the sixth form (years 12 and 13) in curriculum time, and has also started to work with Imperial College on offering the CREST Award for students in year 12, which they carry out in an unoccupied lab in their free periods. For the projects carried out in curriculum time, Aba made a conscious decision to change the way she was teaching required practicals to introduce open-endedness, and plan for progression in problem solving and decision-making.

Who participates?
Aba makes the required practicals open-ended for all A level students. She offers additional CREST Awards to all year 12 students, with 30 out of 40 applying to take part.

Intended learning outcomes
Aba wants students to learn the joy of discovery in science, develop problem solving and analytical skills, to link theory to experimental work and to understand how to test a hypothesis. Students have carried out open-ended work on reaction rates and the identification of ionic compounds.

School support
Technical support - the students can speak to the technicians to request any equipment for their project work.

Advice for teachers interested in doing open-ended investigative projects

- Teach the theory first so students understand.
- Discuss the uses of equipment.
- Make connections with prior learning.

About the school
Westminster City School is a comprehensive academy, educating boys between ages 11 and 16, and girls and boys aged 16-18. Students are offered A-levels post-16, and teachers teach within subject specialism.

Perceived outcomes for students
Students learn how scientists work and about the importance of problem-solving - it "gets students to think differently". Aba is also convinced that it helps the students to rediscover the joys of science, which she thinks can be lost through the formulaic nature of the GCSE syllabus.

Teacher's role in supporting the project
Aba tries to scaffold students' learning, for example by offering a choice of equipment and helping students to work out which is appropriate for the task. By year 13, she tries to get to the point where students can be given a problem and are able to apply theory, design an investigation and select appropriate equipment. For CREST, she encourages students to work in mixed science groups. Laboratories are not fully timetabled so students can - and are expected to - access these in free periods.

"I think it helps better if students have it open-ended, then they are not just following it like a recipe to bake a cake, but they are actually understanding why they are applying certain parts in the method...students will appreciate it"

Fly Lab

Dr Maria Courel, Head of Biology
The Judd School, Tonbridge, Kent

Project description

Open ended investigative project work is offered as part of Fly Lab, a genetics project involving experiments with fruit flies. Year 12 and 13 students are invited to take part in their spare time. It is in its infancy. Students are able to pursue their own interests: they decide the problem or question, the theory or background, the design and procedures, methods of analysis and communication of results, and their conclusions. Maria supervises projects in her lab (open every day after school for an hour) and has created a Google classroom to support the project.

Who participates?

The project is offered to students in years 12 and 13. There are currently about 40 students involved. Maria thinks it is "good for the students to get experience of what science is actually like before, or while they're making choices."

About the school

The Judd School is a voluntary aided state grammar school for boys aged 11-16, and girls and boys in the sixth form. Science is taught within teachers' specialisms. The school offers A levels and the EPQ.

Intended learning outcomes

Maria would like students to learn how to conduct an investigation from start to finish: planning, collection of data and analysis of results. She wants students to "appreciate the challenges and rewards of carrying out their own independent research."

Perceived outcomes for students

Fly Lab is in its early days. Maria expects students to "become more confident in interpreting data, identifying variables, and appreciating why it's important that they do it in a controlled manner."

Teacher's role in supporting the project

Maria sees her role as supporting students to become independent. She organises input from external experts, e.g. academic researcher Dr Camilla Larssen from the Centre for Developmental Neurobiology at King's College, London, and training sessions on the theoretical background. Maria provides practical training on how to handle and analyse fruit flies. She helps students to discuss interesting questions to pursue, and is then hands-off, taking her lead from the students.

School support

Maria works quite independently on Fly Lab in the school context. The project is constrained by access to laboratory equipment and technician time, and the type of investigation the students can do is prescribed by equipment and resources available in school. Health and safety requirements in relation to materials means that it is only possible to work with small numbers at a time.

Advice for teachers interested in doing open-ended investigative projects

- Don't expect it to be perfect when you start - you will learn a lot the first time.
- Find someone with scientific expertise to advise you.

"I hope students will appreciate the challenges and rewards of carrying out their own independent research which might involve troubleshooting, unexpected results, results that open new areas to investigate."

CREST Gold Award instead of a fourth A Level

Martin Hampshire
Physics teacher
Bournemouth School

Project description
Open-ended investigative work is built into the timetable, just as an A level science might be. Students who elect to do CREST Gold in addition to their three A-levels choose their own project, following their own interest, e.g. changes in heart rate due to exercise. Students have individual sessions, 15 minutes per fortnight, during which they get personalised support.

Who participates?
Students who take three A-levels have to choose another course to fulfil the school's requirement for post-16 study matching the equivalent of 3.5 A-levels. CREST Gold (starting in Year 12) is one option.

About the school
Bournemouth School is a selective academy for boys aged 11-16, and girls and boys aged 16-18. Students are encouraged to study four A Levels, or three A levels with a CREST Gold Award, or an additional mathematics or Pre-U humanities course.

Intended learning outcomes
Martin wants students to see what real science is and to learn that science is accessible to everybody. He also wants students to gain the ability to evaluate data and claims, to communicate ideas and to be resilient when initial methods fail.

Perceived outcomes for students
Martin believes that the projects lead to improved motivation and attainment, a better sense of what it means to do science, and greater interest in doing something technical or scientific in the longer term. He has also seen students develop a sense of pride in their investigative project work.

Teacher's role in supporting the project
Martin sees himself in a reactive role, helping students to formulate realistic research questions, to search literature online and respond when students come up against problems. He encourages students to keep a lab book.

School support
- School leaders support and value CREST.
- Technicians' expertise, time and enthusiasm for projects.
- The school librarian teaches advanced literature searching using databases.
- Space - a small lab has been allocated to project work and storing associated equipment.

Advice for teachers interested in doing open-ended investigative projects
Don't underestimate the time and resource needed to offer free-rein on the focus of open-ended projects - students make mistakes, reach dead ends and will need to start again.

"for us it's that second string and for them just making them realise that it's not that they've done the experiment badly and it's not their fault or whatever else but that is what the nature of scientific data is and being able to handle that and cope with it."

Northern hub for the *Institute for Research In Schools*

Nick Harris
Biology teacher (also working with other local primary and secondary schools)

Project description

Nick is responsible for the Northern hub for IRIS. Post-16 students are offered the opportunity to participate in open-ended investigations by doing a real science research project (currently about Motor Neurone Disease studied in yeast). Regular meetings are one hour a week, outside school time, with practical activities run whenever the teacher, technician and students can get together during the school day. Students ask their own questions of data and participate in practical steps with Nick during free periods.

Who participates?

Any A-level student can participate.

Intended learning outcomes

Although individual students may not be able to participate at every level of the practical aspects of the project, Nick wants students to learn what it is to be immersed in a real research experience, under supervision.

Teacher's role in supporting the project

Nick spends much of the project time on discussing the project and its processes with the students, and engaging them with the design of the experiments. He tries to limit it to what the students really need to know to be able to participate.

Advice for teachers interested in doing open-ended investigative projects

Just do it - if you want to create a culture, seminar and journal clubs are quite easy to set up and there are perks for the teacher in the form of involvement with exciting new science, which can help in continuing to feel part of the scientific community and to feel inspired to continue teaching.

About the school

Tapton School is a comprehensive co-educational school for students aged 11-18, offering A Levels. Teachers teach within subject specialism.

Perceived outcomes for students

Nick believes that open-ended investigations help students to apply their A level biology knowledge and to expand students' horizons. He notes that students ask "lots of questions about what could it be and that was encouraging so they are aware of having to think." He also believes that it influences their career decisions.

School support

There is a perception that the school leadership values research, including in the appointment of new teachers. Nick benefits from technical support when he carries out the practical work. Other supporting structures include a research seminar series and journal club.

"The other teachers in the room are just falling over going how can you do that? How do you have time? And I'm like, well, if you teach them stuff that's beyond the spec and it really gives them a deeper understanding then actually they've got a textbook, they don't really need me to tell them what's in that textbook because they can read it themselves."

Antibiotics unlimited

Colin Inglis
Biology teacher and STEM coordinator
Boroughbridge High School

Project description

Students follow their own interests, almost without limits. Many projects are based around finding alternatives for antibiotics, because of the issue of antibiotic resistant bacteria. Starting point is homework, asking relatives about alternatives they have heard about, or remedies they would recommend. Projects run after school, one hour a week. Some projects run for many years, driven by the students as they move up the school. Projects are written up and taken to conferences, not limited to student conferences, and/or entered for CREST Silver Award.

Who participates?

Any student who is interested can take part, and they can work on their project over multiple years.

Intended learning outcomes

Preparing for a future in a fast changing present, Colin feels “they don’t need to be taught knowledge, they need to be taught thinking skills and problem solving skills and creativity and to not be limited by the book and whatever else”.

Teacher’s role in supporting the project

Because Colin does not want to limit the students in any way, he often finds himself out of his depth with the science initially. He uses all his teaching experience and pedagogical knowledge but allows students to go where the project takes them.

About the school

Boroughbridge High school is a community comprehensive school, co-educational for students aged 11-18. Students have provision to study all Sciences to A Level through a partnership with King James's School.

Perceived outcomes for students

A sense of “research culture”, and “when they go to university they’re more confident”.

School support

Technicians and SMT needed some persuading of the merit of the project and the time commitment but were won over by evidence of the value for the students, as well as Colin’s acquisition of time-saving equipment.

Advice for teachers interested in doing open-ended investigative projects

Taking STEM through the looking glass (https://www.ase.org.uk/system/files/SSR%20September%202017%20017-024%20Inglis.pdf)

“you see them when they arrive at a conference and by the end of the conference they’re about six foot taller and they’ve got all the communication skills and the confidence, they’ve got the vocabulary, and they’re then communicating their science and they are the scientists for the moment… gives them something to talk about when they go to interviews and apply for colleges and universities”

IB Internal Assessment

Paul McDaid
Head of Science
Tonbridge Grammar School

Project description

Open ended investigative project work is carried out as part of the IB Diploma Programme in which students are required to complete internal assessment. This is based on one scientific investigation lasting approximately 10 hours, which the school schedules in a day off-timetable following year 12 exams. Lunch time and after-school sessions are offered to help complete laboratory work. Students are able to pursue their own interests. Projects have included an investigation into the difference in water hardness across the UK (the student received postal water samples from relatives across the country) and the creation of lab-based model of ocean acidification by investigating the impact of pH on rate of decomposition of calcium carbonate.

Who participates?

Almost all sixth form students. The internal assessment for most of the IB DP group 4 subjects is an open-ended investigative project worth 20% of their mark for the subject.

Intended learning outcomes

Paul would like his students to learn "how to conduct practical work using manual dexterity". He also wants them to gain "planning and organising skills, ability to manipulate data, reach conclusions and evaluate processes."

Teacher's role in supporting the project

Paul sees his role as supporting students to pursue their own interests but at the same time ensuring that the project they design is feasible. Paul gives students the chance to practise research design and data handling, and gives feedback on early plans.

Advice for teachers interested in doing open-ended investigative projects

- Allow students the opportunity to come up with their own ideas.
- Provide students with a list of 'tried and tested' practicals and encourage them to manipulate the variables.

About the school

Tonbridge Grammar School is a selective grammar school with academy status, educating girls aged 11-16, and girls and boys in the sixth form. Teachers teach within their specialism. The IB is taught exclusively at sixth form.

Perceived outcomes for students

According to Paul, the main outcomes are that students can "think independently, they have the ability to approach a problem and find a way through it to see whether it actually works."

School support

Paul identified a range of support that the school provides, most notably providing extended timetabled time in the summer term for investigative work.

"I think there'll be a knock-on effect to researchers in the future. Yes, not all of our schoolchildren are going to be scientists, but for that percentage that are I think it's important that we give them an opportunity to develop their handling skills, to develop their skills, but also to understand what they're doing, and why."

Summer with woodlice

Simon Moore
Biology Teacher
Wymondham High School

Project description

Open-ended investigative project work on woodlouse behaviour is carried out in summer term at the end of Year 12. Students spend approximately six weeks (15-18 lessons) conducting an investigation into woodlouse taxis and kinesis. Simon introduced the projects because he believed that students were missing important learning opportunities following the move away from investigative work in examination specifications. Students investigate the same subject area, but ask different research questions and designing projects in different ways.

Who participates?

All A Level Biology students

Intended learning outcomes

Simon wants students to learn the value of ownership of a research question, and to appreciate the challenges with doing research. He thinks it is important for students to learn the need for a large volume of data, how to control variables, and how to use statistics.

Teacher's role in supporting the project

Simon sets the project up by introducing some theoretical background to the behaviour of woodlice. He provides students with methods and analytical techniques, but students are not provided with the question or problem they will investigate, although they can use examples of investigations from previous years as inspiration.

Advice for teachers interested in doing open-ended investigative projects

Simon encourages interested teachers to find a topic that interests them and just get started.

About the college

Wymondham High School is an 11-18 co-educational academy in Norfolk with approximately 1600 students on roll. Post-16, Wymondham High offers A Levels.

Perceived outcomes for students

Simon believes that the projects enable students to understand how to ask a good research question, i.e. to understand the scientific context and find out what is already known. Simon's students learn how to make decisions about experimental design. Simon feels the projects allow students to get to grips with scientific referencing, and to learn the relative value of internet references and references from books.

School support

The school offers technical support for the project (technicians look after the woodlice). Post-16 results are good, students enjoy the investigations and they are perceived to be a good use of time, which releases the pressure to start teaching the year 13 course after year 12 exams.

"I do it because it's the only opportunity that they get to do any real science: to take a problem, find out about it and then come up with an answer. What matters is they give it a go and it's a real question that nobody knows the answer to."

Redox titrations, Salters' style

Lisa Niven
Chemistry teacher
All Saints Roman Catholic School

Project description

Redox titrations involving iron. Open-ended, but limited student choice - teacher sets context, students work in groups and are assigned a food group, after which they choose their own specific food to investigate individually. Bake-Off style information/recipe provided to students, including balanced equation(s) for stoichiometry. Curriculum time, for two to three weeks, allocated just before the summer holiday in year 12. Students may spend additional time in the lab during free periods, lunch and after school, depending on lab space and supervision availability.

Who participates?

All A level Chemists, even if they do not pursue the full A level; some of those drop out due to AS results and their future plans.

Intended learning outcomes

Lisa wants students to "learn to be resourceful", and to get a good taste of collaboration, talking through problems, and in the process of writing about experimental work. There should be opportunities to learn from mistakes, and to gain an understanding that that is a common and useful trait in scientists.

Teacher's role in supporting the project

Facilitator, with minor scaffolding, sometimes referring to students' lab books of earlier work. Signing off plans, including risk assessments. Guidance provided on the kinds of questions that need to be answered in a report, but encouraging peer discussion about all aspects.

Advice for teachers interested in doing open-ended investigative projects

Probably unwise to try before the summer term in year 12, as you need to know your students fairly well. It would make sense to have an example, say from Salters or Nuffield, and expand that. "Don't reinvent the wheel."

About the school

All Saints Roman Catholic School is a comprehensive school, co-educational for students aged 11-18.

Perceived outcomes for students

Build a community of A-level students, from what were disparate and separate classes. Students build confidence, become "more willing to ask questions". Potential for positive impact on the students' CPAC endorsement and the substance of a UCAS reference. Opens some students' eyes to other options out there (e.g. dietician rather than scientist or doctor).

School support

Head technician outlines health and safety expectations at start, shows possible equipment, supports with restocking supply of chemicals. A supportive department, willing to move around, allows for one lab dedicated to the projects, as long as it can be supervised by a chemist and does not overrun capacity ("one out, one in policy").

"Don't be afraid to try it. I think that would be the big thing, is that it's very scary to try something as big as this, particularly if you've never done it before and you don't have somebody to support you. But the gains far outweigh the risks I think."

A legacy of Advancing Physics before the linear exams

Simon Poliakoff, Head of Physics and Specialist Leader in Education
Dame Alice Owen's School

Project description

Following the loss of coursework from the A level specification, the Physics department decided to reintroduce open-ended projects during the weeks before the summer holidays at the end of year 12. Students chose from around a dozen projects on which to base their own investigations, from new contexts for understanding simple harmonic motion to the Hall effect. They work individually or as a pair. Students have an hour long introductory session, five hours of practical work supplemented by homework then two hours to create a conference-style poster.

Who participates?

All A-level physicists participate. The school's biology and chemistry departments do not have a legacy of open-ended coursework as part of their earlier specification, and do not currently offer similar projects with biology or chemistry students.

About the school

Dame Alice Owen's School is a partially selective mixed academy supported by The Worshipful Company of Brewers of the City of London. The sixth form curriculum comprises solely of A levels and teachers teach within specialism.

Intended learning outcomes

Simon intends students to learn how to manage their time over multiple practical sessions, how to progress an investigation beyond an initial plan, how to choose suitable graphs to plot and test relationships and how to present a conference-style poster.

Perceived outcomes for students

Examples of outcomes corresponded with what students needed to succeed at A level, but more besides. Simon felt that students gained experience in making decisions about their project and managing their time over a longer project.

Teacher's role in supporting the project

Simon starts students off with a question and some suggested references. He sees his role as a guide through the problems that might crop up, either from a sub-optimal design or from sub-optimal results. Simon shares possible projects via Google drive, reads plans in advance, speaks to students, provides training where needed, troubleshoots and teaches related practicals so that students can plan their own method for a related question.

School support

All physics teachers are involved with the open-ended projects, working together to prepare the projects and supervise students with support from a good specialist technician. Removal of AS exams has provided a time for students to do their investigations and freedom from having to do investigations as coursework has enabled teachers to support a wider range of projects, and given more scope for students to iterate and greater flexibility in how findings are presented.

Advice for teachers interested in doing open-ended investigative projects

It is easier to start by having a list of 10-12 suggested titles and references, because students often stagnate when given a completely open choice.

"It's now no longer a coursework, though we were using it as further evidence of feedback criteria as the investigative skills as the practical endorsement."

Planting ideas in plant biology and psychology

Richard Spencer
Head of Science
Middlesbrough College

Project description

Richard does different projects each year, depending on his interests and opportunities available at that time. The project that ran this year was linked to a visit to Dilston Physic Garden with the Royal Society of Biology and the SAPS plant summer school. It took place for an hour a week over a period of about 4 months, in parallel with fieldwork planning. Students were given experience of experimental design and open-ended investigative work in the context of herbal teas, oils or tinctures and then investigated the effect of herbal essential oils on memory. Richard designed the project in collaboration with Dr Nicolette Perry, a pharmacognosist and director at Dilston Physic Garden, following a discussion about memory and plant essential oils.

Who participates?

A level biology students.

Intended learning outcomes

Richard wants his students to learn about "real science and to experience how research raises further questions, how to design a research project that is feasible and how to process data".

Teacher's role in supporting the project

Richard says that "first and foremost you have to be enthusiastic about it yourself." To do that, Richard feels the need to have good background knowledge himself. Richard presents students with a brief and a related research study, and then students decide on their question, method and all that follows. Richard shares his experience in research science with students, empathising when they experience problems.

Advice for teachers interested in doing open-ended investigative projects

- "Take the risk and the results will speak for themselves."
- Use open-ended projects to develop CPAC related skills.
- Work in partnership so that you have somebody to help with the development and share ideas.

About the college

Middlesbrough College is a large further education college for students aged over 16. There are 14,000 students on roll. A wide range of post-16 science courses are offered, including A levels, vocational courses and apprenticeships. Richard teaches within the sixth form directorate.

Perceived outcomes for students

Richard identified a range of gains for students including developing an interest in and enthusiasm for science (particularly plants), to understanding how research works and making A level content more meaningful. Richard also identified more instrumental gains, including distinctive experiences that can be used in UCAS applications.

School support

Richard does not have protected time for carrying out projects: he squeezes projects into his spare time and class time. Technicians provide support in designing new approaches to practical work and advice on health and safety.

"To be a great teacher you have to be a great learner and your students need to see that you're learning…that's one of the most important things about investigative work. You're not just doing an experiment: you're exploring; you're finding out together and you don't know what the results will show."

Real World Chemistry

Stuart Strathdee
Greenhead College
Huddersfield

Project description

Open ended investigative project work is offered through Real World Chemistry, an enrichment project open to all year 12 and 13 students. Students rank their preferred projects following short presentations from the University of Huddersfield's School of Applied Sciences. Stuart then matches up students' interests with a research group, paying attention to making sure each group has students in different year groups with different strengths. Students work together with the university staff to review research and some carry out data collection in their area of interest. These included projects on carbon capture and industrial processes and safety. Projects typically involve students working across disciplines, for example a project on solar cells involved applying knowledge of electronics, organic chemistry, and polymers.

Who participates?

Sixth form students in years 12 and 13 work in groups. In 2017/18, 28 students participated. Of these, 24 are now studying for STEM related degrees. Using ALPS, these students made outstanding progress (high grade 2).

About the college

Greenhead College is a sixth form college educating young people aged 16-18, primarily offering A level as well as the Extended Project Qualification. There are currently about 880 students studying A level chemistry.

Intended learning outcomes

Stuart wants students to learn research, analytical, presentation and team-working skills, as well as to gain an appreciation of interdisciplinarity and of chemistry in the world, in relation to the political, economic, social, technological, legal and environmental context.

Perceived outcomes for students

Stuart has seen "massive boosts in confidence" and has had many students go on to STEM degrees. Stuart reports that the projects help student to work as part of a group, to present findings in a professional setting and develop employability skills.

Teacher's role in supporting the project

Stuart sees his role as a facilitator of the projects, making sure that they are making progress each week and liaising with the university. Stuart teaches students how to find abstracts using public domain search engines, how peer review works, and how to judge the validity and reproducibility of research studies and supports students to interpret scientific papers.

College support

The college day currently allows some extra non-contact time for staff to develop new enrichment activities, and all teachers are expected to contribute to an extracurricular activity. The intellectual space to focus on the project comes from being able to specialise as a teacher of chemistry and to discuss ideas with chemistry specialist colleagues.

Advice for teachers interested in doing open-ended investigative projects

- Organise regular timetabled meetings.
- Involve a colleague to share work and ideas.
- Share goals with partner organisations.

"I think it's really important they realise how collaborative and how interconnected all real research is. [Real World Chemistry] did make them realise how many people and how many different fields contribute to advances."

Meeting the challenges associated with open-ended investigative projects

Teachers in all schools and colleges identified challenges that they had experienced themselves, or that colleagues had shared with them in relation to doing (or not) open-ended investigative projects. These fell into three main categories: challenges associated with the external policy context, the student experience, and school infrastructure. The teachers we spoke to tended to focus on solutions when they were asked to identify barriers or challenges. The challenges have been matched with responses from teachers within the sample, demonstrating different approaches to overcoming perceived and actual challenges associated with offering open-ended projects.

Challenges associated with the external policy context

Challenge	Response
Curriculum and assessment Open-ended investigations are not thought to be valued in the way science is examined. Teachers reported that assessment regimes often encourage 'spoon feeding' and as a result students struggle to think critically and understand scientific methods.	● Teach a curriculum that values open-ended investigative work (e.g. the IB or BTEC). ● Value investigative work by timetabling lessons leading to a recognised award (e.g. CREST). ● Use open-ended investigations as evidence for students' practical endorsement. ● Encourage critical thinking and engagement with scientific methods in a low-risk context through open-ended investigative projects.
Health and safety Many more students want to participate in the projects than a single teacher can cope with for some projects where procedures are hazardous. Projects which give students free choice over topic and design require individual risk assessments, which is an additional workload for teachers. New investigation areas require trialling and new risk assessments.	● Carry out some steps as an extra-curricular activity with a small number of students ● Constrain choice e.g. to a small number of techniques. ● Ask CLEAPSS and equipment manufacturers for support where beyond the usual scope. ● More experienced colleagues supported less experienced. ● Test ideas out alone or with a technician during the holiday. ● Ask technicians or PGCE students to search, test and refine procedures.
Funding for staff time Lack of acknowledgement or recognition for teacher and technician time in departmental and institutional workload models, and funding models, including school funding and grants for project work in schools.	● Teachers responded by working voluntary beyond their timetabled hours. ● One teacher had been involved in a larger scale project that paid for teacher time. ● Treat open-ended project time as any other timetabled subject. ● Encourage students to write about open-ended investigations in UCAS applications. ● Relieve teachers who run open-ended investigations from duties.

Challenges associated with the student experience

Challenge identified	Response: what teachers did
The academic demand of projects can be seen to be a distraction from meeting exam specification requirements.	● Treat investigations as a means by which students can apply knowledge and develop a deeper understanding of specification content, particularly in relation to the examination of 'required practicals'. ● Use projects to demonstrate that students have met the CPAC for their practical endorsement. ● Teachers argued that open-ended investigative projects had a positive impact on attainment at A level and on their ability to make more informed career decisions. ● Use school data sets (e.g. ALPS) to compare cohorts doing project work with those who are not to monitor impact on attainment.
It can be challenging for students to cope with and interpret unexpected results. Some students find this difficult, or even demoralising.	● Empathise by sharing their own experience of investigations in industry or academia. ● Demonstrate that they are learning outside their comfort zone too. ● Explain this as a characteristic of doing real science.
The level of mathematical or statistical demand was often greater than had been taught.	● Provide workbooks applying mathematics and statistics in scientific contexts from the beginning of the course. ● Teach statistics and ask students to apply in new science contexts through open-ended projects.
Students sometimes struggle to understand scientific methods.	● Use open-ended investigative projects as a way of teaching about real science, research design, data handling and analysis. ● Encourage collaboration between students in different year groups by offering after-school support.
Motivation at the end of year 12 in summer.	● Offer an open-ended project where students have freedom to investigate something of interest to them.
Instrumental approaches to learning, some students reluctant to learn beyond the specification.	● Use open-ended investigations as evidence for students' practical endorsement. ● Model enthusiasm, love of learning and interest in finding out about the world or solving a problem.
Students are very good at recall but have had little practice at handling data at GCSE.	● Create opportunities for students to experience data handling through low-risk open-ended investigative projects.
Not all students can access extracurricular project work.	● Create opportunities for project work in class time, particularly at the end of year 12.

Challenges associated with infrastructure

Challenge	Response: what teachers did
Scientific literature and other sources are often inaccessible to students e.g. recent papers are behind paywalls.	● Collaborate with university colleagues, who provided access to students. ● Subscribe to journals such as Chemistry Review.
Access to external partners.	● Those in cities were able to draw on STEM Ambassadors and university scientists.
Equipment available in school constrains students' approach.	● Seek internal (e.g. PTA) and external (e.g. Royal Society) funding. ● Liaise with a local university. ● Ask for equipment (e.g. ex-display models.)
Space. Many schools and colleges were previously able to use a spare laboratory for project work.	● Designate a single laboratory as a 'project lab' for part of the year; protect this in the timetable. ● Redeploy small classrooms no longer suitable for larger class sizes.
Time-boundedness. Fitting extended investigative work into timetabled lessons is challenging.	● Request additional timetabling in the summer term when students are often out of class doing exams, on trips or conducting fieldwork. ● Encourage 'kitchen' or home science, with students bringing data or samples to school.
Student numbers. Open-ended projects generate a lot of (different) questions for the teacher; specialist equipment cannot be used by large numbers at once; consumables are expensive for large cohorts of students.	● Start small by offering an optional project or club, move into timetabled time as experience is gained. ● Allocate a weekly slot when students are free and involve other colleagues. ● Involve other teachers of the same subject to co-plan and share supervision duties. ● Enlist technicians, visiting students, PGCE students and NQTs to support students' projects. ● Constrain choice: identify familiar procedures that can be adapted to new contexts. ● Allow pair or group work. ● Rotate project work with other non-practical work during the summer term.
Technicians: some schools have few technicians, or a high turnover.	● Train students to do their own technical work. ● Make the case for greater technical support.
Teacher inexperience or lack of expertise in students' areas of interest.	● Shadow a more experienced colleague ● Seek support, e.g. from local universities via an outreach officer or STEM ambassador. ● Model learning alongside students. ● Transfer responsibility for most of the work to students - adopt a responsive role.

Subject-specific observations

Most teachers in the sample taught within their specialism at key stage 4 and above, and the projects they offered post-16 tended to be within specialism. Here, subject-specific considerations are discussed. Teachers who offered projects that cut across specialisms tended to work with others with complementary expertise, whether researchers working in a university context or teachers with a different scientific background (most notably psychology).

Biology projects

A distinctive feature of some biology projects was that they involved working with living organisms including bacteria, flies, woodlice and human subjects. This raises a number of issues for teachers, most notably the ethical issues, and the health and safety considerations needed in order to house and carry out research on living organisms. Some projects had resulted in novel solutions to dealing with health and safety issues that had arisen during open-ended investigative project work. Having ownership of a lab was an important enabler of biology projects as this allowed the teacher responsible to store resources such as apparatus between use with students. Teachers identified students' statistical knowledge as a conceptual demand of biological projects.

Chemistry projects

For chemistry projects, the legacy of specifications requiring open-ended investigative projects was evident, with teachers drawing on their experiences of successful SAC projects.

Although health and safety considerations were important across all projects, this was most notable in chemistry projects. Indeed, the demand of risk assessments for open-ended projects was identified as one of the key reasons why chemistry projects were not hosted in a school where they were offered in other sciences. Chemistry teachers in the sample dealt with workload associated with risk assessments in a number of ways, for example by constraining students' choice of procedure and reagent, or involving technicians and other teachers in projects. Similarly, access to specialist (and often expensive) analytical equipment was important for chemistry projects, and universities played a role in providing access to equipment or offering analysis of samples for school students conducting open-ended investigative work. For projects using only school equipment, the set-up and clear-away time needed for wet chemistry projects was an important consideration given timetabling constraints.

Mathematical demand appeared in these projects, most notably for stoichiometric calculations and logarithms, and some teachers had built applied chemical mathematics into their A level programmes as a separate, independent strand of work.

Physics projects

The legacy of exam specifications requiring open-ended investigative projects was evident for some physics teachers, who were building on the legacy of SHAP. They constrained choice, allowing students to select projects of varying levels of demand in terms of subject knowledge or manipulative skill. Also important for the physics projects was mathematical competence.

Conclusions and limitations

This report draws on case studies a small sample of teachers doing open-ended investigative project work. Open-ended investigative projects are defined as tasks in which students design an experiment to test a given question, carry it out and interpret the results, all within a fixed time period (Gatsby, 2017). All teachers in the sample valued open-ended investigative project work to the extent that they were willing to dedicate their own non-directed time, and indeed personal time, to supporting it. Teachers allowed all students in their school to access open-ended investigative projects, regardless of prior attainment.

How do science teacher approaches to practical, open-ended and extended investigative projects vary? All projects were unique in one or more of the following dimensions: subject, extent of open-ness for students, use of external support, duration of the project, amount of class time dedicated to the project, involvement of technical staff, use of research literature, assessment, and presentation of findings. Where they could, teachers found ways to formally recognise their students' work.

What do teachers want students to learn by carrying out open-ended investigative projects in science, and how do they bring this about? Teachers had clear intended learning outcomes for open-ended investigative project work, most significantly, learning to do 'real' science, understanding the state of the field, research design, data handling and iteration. Each teacher had additional learning outcomes corresponding to their specific project. Preparation for university and the UCAS process was also important. Teachers tended to introduce the context at the outset and move towards a hands-off, responsive mode of teaching. Some teachers scaffolded practical work over year 12 towards independent investigative work.

How do teachers see their role in supporting students to carry out open-ended investigative projects in science? Teachers saw their primary role in planning and introducing the project, facilitating student choice and learning, ensuring risks were minimised and that the work complied with health and safety requirements, networking with external organisations and responding to students' needs.

What enables successful project work in schools or colleges, and what barriers exist? Common barriers to open-ended investigative project work in curriculum time were teacher time (required of teachers to plan projects, assess risks and support students on an individual or group basis), school timetabling, the level of demand for students, student motivation, and instrumental attitudes, whereby activities were valued in relation to how likely they are thought to influence examination success. For some, lack of teacher expertise was considered a barrier. Resources such as access to literature, lab space, equipment, technical support and external expertise also acted as barriers, particularly in some locations. All teachers in this study had found ways of negotiating barriers. Enablers of open-ended investigative work related to the teacher (experience, freedom), the department (availability of technical support), senior school leadership (resources, policies, deployment of staff and space), specifications, and external support and recognition (STEM ambassadors, CREST Awards, grant funding).

It was difficult to find teachers who carry out project work in class time, and as a result the report draws on a small number of teachers who were currently doing open-ended projects. No teachers in the sample discussed open-ended investigations in the context of outdoor learning or fieldwork; nor based largely in university outreach laboratories nor as contributing to an EPQ. Only teachers in state schools were included in the sample, and all were working in institutions graded 'good' or 'outstanding' by Ofsted. All had at least 5 years' experience, with the majority having more than ten. All of the teachers had negotiated challenges successfully to greater or lesser degrees. There are likely to be teachers in more challenging contexts, with less experience who experience different barriers.

Recommendations

Teachers

Practical suggestions for making open-ended investigative projects possible:

- Use open-ended projects as a way of teaching required practicals and providing opportunities to meet the CPAC.
- Plan in advance: identify good candidate practicals that can be made open-ended. Ask a PGCE student or NQT to help with this work.
- Take it slowly - try it with one group and work through any teething problems.
- Enlist technical support in refining procedures.
- When you get stuck, contact a scientist - universities are generally willing to help teachers.
- Students' work can be recognised with CREST Awards - this can help convince school leadership that open-ended investigations are valuable.
- Request different timetabling arrangements for the summer term to facilitate extended investigations.

Schools

Schools can take a number of steps to make open-ended investigative work possible:

- Adopt curricula that require open-ended investigative work.
- Ensure the staffing, estate and funding of science departments is adequate to provide opportunities for open-ended project work.
- Give science teachers autonomy, particularly after examinations (where they exist) in the lower sixth (year 12).
- Value teacher time by timetabling open-ended investigative work and counting in workload models.
- Adopt flexible timetabling models, e.g. allowing for periodic collapsed days for open-ended project work and releasing teachers to plan and supervise projects.
- Fund technical support for open-ended investigative work.
- Encourage teaching within specialism, and specialist technical support.

Systems

A number of systemic changes are likely to support making open-ended investigative projects possible:

- Teacher and technician buy-out for collaborative projects could be funded.
- Inclusion of open-ended and extended investigative work in examination specifications.
- Extend/formalise networks (of people, portable equipment) across England to ensure that schools in all areas have access to STEM expertise.
- Work with examination boards to develop exemplar material for demonstrating students meet the CPAC through open-ended investigative work.
- Commission research to investigate the impact (if any) of open-ended investigative work on post-16 attainment.

References

Bennett, J., Dunlop, L., Knox, K. J., Reiss, M. J., & Torrance Jenkins, R. (2018). Practical independent research projects in science: a synthesis and evaluation of the evidence of impact on high school students. *International journal of science education*, *40*(14), 1755-1773.

Buck L. B., Bretz S. L. and Towns M. H., (2008), Characterizing the Level of Inquiry in the Undergraduate Laboratory, *Journal of College Science Teaching*, 38, 52-58.

Cramman, H., Kind, V., Lyth, A., Gray, H., Younger, K., Gemar, A., Eerola, P., Coe, R. & Kind, P. (2019) 'Monitoring practical science in schools and colleges.', Project Report. Durham University, Durham.

The Gatsby Foundation (2017) Good Practical Science. London: The Gatsby Charitable Foundation.

Gott, R. and Duggan, S. (1995) Investigative work in the Science Curriculum. Buckingham: Open University Press.

Loughran, J., Berry, A., & Mulhall, P. (2012). *Understanding and Developing ScienceTeachers' Pedagogical Content Knowledge* Vol. 12. Springer Science & Business Media.

Appendix 1 Questionnaire

Teaching through open-ended investigative work
(Adapted from Google Forms)

A research team from the Department of Education at the University of York is carrying out a project on the teaching of open-ended investigative project work with post-16 students. We are interested in finding out what teachers intend students to learn (and how they design learning experiences to achieve this) when they do open-ended investigative work with post-16 students. By open-ended we mean that although the outcomes may be known to the teacher, they are not known to the students.

The research will involve the following brief survey in combination with semi-structured interviews to be held later this year. If you do open-ended investigative work with your students and are able to help by taking part in an interview later this year, please would you answer (briefly) the questions on this survey using short sentences or bullet points. Please direct questions to Dr. Maria Turkenburg (maria.turkenburg@york.ac.uk) or Dr. Lynda Dunlop (lynda.dunlop@york.ac.uk).

1. What concepts or ideas is it important for students to know in order to do successful open-ended investigative work?
2. What do you intend students to learn through open-ended investigative work?
3. Please state whether or not you provide the following to the student(s) when you do open-ended investigative work with them. For example, if students were responsible for developing their own procedures, select 'NOT provided to students' for 3. Below.

	Provided to students	NOT provided to students
1. Problem/Question		
2. Theory/Background		
3. Procedures/Design		
4. Analysis of results		
5. Communication of results		
6. Conclusions		

4. If you are happy for us to invite you to a follow-up interview, please select 'Yes' below.
    - Yes
    - No

Thank you for your time. Your responses to these questions will inform the interview questions we ask later in the year. If you would be comfortable doing so, please forward the link to this survey to anyone you know of who carries out open-ended investigative work with students.

Appendix 2 Interview guide

Contextual questions

- How long have you been teaching A level science in England?
- What do you consider your specialism? What is your highest qualification in the A level science subject you are teaching?
- What exam board specification do you follow? Why? Do you have experience of others?

Questions about what teachers do to support learning (for each key idea identified from the pre-interview question: 'real' science; data handling; research design; state of the field and iteration)

- Why is it important for students to learn this?
- [How did you learn to do this? Where would you go to find out more about this?]
- What else do you know about this that you don't intend students to know yet?
- What are the difficulties or limitations for a teacher associated with teaching this idea?
- What knowledge about students' thinking influences how you teach this idea?
- What teaching procedures or strategies do you use? What are your reasons for using these?
- What other factors influence how you teach this idea? For example, knowledge about how students think or how they learn science influences how you teach this idea?
- What strategies do you use to ascertain student understanding or confusion around this?

Questions about the practical open-ended extended investigative project

- Please describe the nature of the practical open-ended extended projects you do with sixth-form students.
- [ask for examples of stimulus or other materials provided to students]
- [Remind of responses to levels of inquiry question]
    - For the dimensions that were provided, how are they provided?
    - For those that are not provided, how are students supported to do this independently?
- How long have you been doing these?
- [if in an 11-18 school] is project work common in science at KS3 and KS4?
- Why did you start doing these? Why do you continue?
- Do you expect the whole year group to undertake projects or just some? If it is optional which students tend to choose to do them and why?
- Is there any conceptual knowledge required for students to participate in the project? How do they gain this?
- How do you see your role in practical open-ended extended investigative projects?
- How do you supervise and manage these?
- How do you work with other members of the science department, or school, to deliver this (teachers, technicians)?
- How do you know the extent to which you have been successful in promoting learning? [probe how they assess students' knowledge or practice – if you do assess students]

Concluding questions

- What advice would you give to a teacher considering doing these projects?
- What conditions do you think are needed for practical open-ended extended investigative projects to be successful? [might need some probes here – facilities, technicians, teacher CPD, expectations of awarding organisations…]
- What, if any, challenges have you experienced? (How) did you overcome these?
- What can students do differently as a result of carrying out practical open-ended and extended investigative work?
- How do you see practical open-ended extended investigative projects contributing to the aims of post-16 science education?
- Is there anything else you would like to tell us about practical open-ended extended investigative projects?

Notes on key ideas

These are the key ideas that teachers who participated in the questionnaire identified as intended learning outcomes of open-ended investigative project work.

Real science

This idea refers to the sense that open ended investigative projects give students the chance to find out about 'real' science, or work more similar to the things scientists do.

Data handling

This idea refers to several aspects of data handling that are important for students to learn about including evaluation of data and claims by others, decisions about data collection (including how decisions are made about the suitability and adequacy of data), data analysis, interpretation and data presentation (for example statistics and graphs).

Research design

This refers to the decisions students make about the methods they will use to carry out a project that answers a research question. This includes decisions about experimental design, the methods of data collection and analysis, equipment, safety and ethics.

State of the field

This idea relates to learning about how knowledge is created in the discipline, including how to search, and review the research literature and understand how their work contributes to understanding the state of the field.

Iteration

This refers to the repetitive and recursive (rather than linear) process linking data collection and analysis during which students might notice unexpected results, test procedures, gain experience of trial and error, or make amendments to their methods.