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https://doi.org/10.1080/09500693.2020.1778211

Open-ended investigations in high school science: teacher learning intentions, approaches and perspectives

Journal:	*International Journal of Science Education*
Manuscript ID	TSED-2019-0461-A.R3
Manuscript Type:	Empirical Research Paper
Keywords:	learning outcomes, practical work, teacher actions
Keywords (user):	open-ended investigation

Open-ended investigations in high school science: teacher learning intentions, approaches and perspectives

Open-ended investigative work is important for science at the high school level because it provides students with experiences approaching the authentic practice of scientists. In the English context, some teachers continue to provide opportunities for open-ended investigation, even though at post-16 (pre-university) A Level students are no longer required to do so. This qualitative study had two aims: to identify teachers' intended learning outcomes for open-ended investigations, and to understand the different ways that teachers perceive, interpret and teach open-ended investigative projects in science. Questionnaires (n=17) and in-depth, semi-structured interviews with high-school teachers (n=12) were used. Analysis of the questionnaire data suggested five 'key ideas' related to teachers' intended learning outcomes for open-ended investigations: state of the field, research design, data handling, iteration, and 'real' science. The interviews revealed teacher repertoires for addressing learning relating to each of these key ideas. Phenomenographic analysis of the interview data suggested six qualitatively different ways of perceiving this work, which corresponded to different emphases for student learning: the teacher-scientist perspective, the teacher-inquirer perspective, the instrumentalist perspective, the independence-builder perspective, the scaffolder perspective and the personal developer perspective. The findings are expected to be useful for informing teacher professional development and reflection, and for those developing curricula, teaching materials or assessments involving open-ended investigation.

Background

Open-ended investigation provides a context for understanding the role of empirical evidence in science, and as such has been advocated on the grounds that it supports students to understand the nature of science and makes science education more authentic, i.e. aligned with the practice of science (Roberts, Gott & Glaesser, 2009). It is thought that open-ended investigations prepare students for future engagement with science, which is considered desirable at both secondary and tertiary levels in science education (Bencze, Bowen & Alsop, 2006; Berg, Bergendahl, Lundberg & Tibell, 2010). In this article, we first define investigation and outline the existing policy context in England, before describing the range of possible outcomes of open-ended investigation and examining the role of teacher beliefs and practices in teaching investigation.

Defining open-ended investigation

The meaning of 'inquiry' has been debated since it was proposed as a teaching strategy by Dewey (Barrow, 2017). Minner, Levy and Century (2010) note that 'inquiry' is used in at least three different ways in the science education literature: it has been used to refer to what scientists do, how students learn, and to pedagogical approaches employed by teachers. What binds these ways of using inquiry together is the asking of questions and seeking into the answers. In this study, we are interested in teachers' pedagogical approaches. At a broad level, inquiry is related to activities that support students to understand scientific investigation including how to ask and answer questions (Krajcik et al., 1998). In a review of 138 research studies, Minner, Levy and Century (2010) recognise the multitude of definitions of 'inquiry' in the context of science education. They describe inquiry as including "science content, student engagement with the content, and student responsibility for learning, student active thinking, or student motivation *within at least one component of instruction*" (p. 5). They focus on investigation as the cycle involving question generation, experimental design, data collection, conclusion and communication of findings. Similarly, Buck, Bretz and Towns (2008) proposed that inquiry work can be classified depending upon which of six characteristics are provided to the students. These six characteristics are the problem or question, theory or background, procedures or design, analysis of results, communication of results and conclusions. Their framework provides a tool for characterising inquiry according to the degree of student independence. In this study, we consider work in which at least one of these characteristics is not provided to be 'open'. This definition is used in order to reflect the fact that not all investigation is of an experimental nature (Wong & Hodson, 2008), and that different parts of the investigation cycle can be open to student decision-making.

Open-ended investigation and the English curriculum post-16

There is currently no requirement for most students to be offered the opportunity to do such work in England. A levels are the most common post-16 pre-university qualification in England (Department for Education, 2019). Whereas students were previously able to gain credit for open-ended investigative work (and still can if they have the opportunity to study other curricula such as the International Baccalaureate Diploma Programme and Business and Technology Education Council courses), there no longer exists a requirement for work of an open-ended nature at A Level. In 2015 (Department for Education, 2015), new rules were established for A level qualifications, introducing a) a requirement to be observed doing 12 hands-on practical assignments, not included in a student's final grade, but contributing to a practical endorsement – 'pass' or 'not classified'- presented on the certificate alongside the grade; and b) indirect assessment of practical skills, worth 15%. Whilst teachers may opt to provide opportunities for students to obtain the practical endorsement through open-ended investigation, there is no longer a requirement for students to gain experience of investigative work of an open-ended nature in order to pass the A level. Few teachers in England now offer open-ended investigative work post—16 (Cramman et al., 2019). Nevertheless, some teachers continue to create opportunities for students to engage with open-ended investigations, often in association with external organisations such as the Institute for Research in Schools (Rushton & Reiss, 2019) or the British Science Association (Moote, Williams & Sproule, 2013). In the sections that follow, we review the research literature on student outcomes from open-ended investigation, and on teachers' beliefs and practices in relation to open-ended investigation, before justifying the purpose of this study: to find out what perspectives exist in relation to open-ended investigation, and to determine what teachers intend students to learn through open-ended investigation, and what they do to bring this learning about.

Open-ended investigation and student outcomes

Research on inquiry learning has been prominent over the past decade (Lin, Lin, Potvin & Tsai, 2018). In the review of 18 years of research into inquiry-based science instruction mentioned previously, Minner et al. (2010) found a trend towards inquiry-based instruction reported in research literature, with the majority of studies carried out in the USA, noting that there is often poor articulation of the amount of teacher involvement in direction and decision-making in inquiry approaches.

Reported outcomes from open-ended investigation tend to be positive and project-specific, relating to affective outcomes such as confidence and self-efficacy (Moote, Williams & Sproule, 2013), attitudes to science (Welch, 2010), conceptual understanding (Krajcik & Blumenfeld, 2006), or views about the nature of science (Metin & Leblebicioglu, 2011), amongst others. In the study by Minner et al. (2010) described at the outset, indications were found that instruction involving investigation (i.e. generating questions, designing experiments, collecting data, drawing conclusion, and communicating findings) has been associated with improved student content learning, especially learning scientific concepts, particularly where there has been an emphasis on active thinking or students taking responsibility for their learning. Whilst Minner et al. (2010) found that just over half of the studies included in their review reported positive impacts of inquiry on student content learning, the outcomes in focus for the study were (i) student understanding of science concepts, facts, and principles or theories; and (ii) student retention (a minimum of 2 weeks after treatment) of these science concepts, facts, and principles or theories. These outcomes might not correspond to teachers' intended learning outcomes for such work. Rather, they may correspond to the intended outcomes of a provider (e.g. a science centre, university partner, or funder, depending on how the open-ended investigation is administered). One of the challenges associated with assessing claims about effectiveness is clarity about what knowledge can reasonably be expected to be gained through open-ended investigations, what teachers' intended outcomes are, and assessing the effectiveness of approaches on this basis. In a more recent review of independent research projects, a type of open-ended investigation in which the students do authentic research, often involving external partners (Bennett et al., 2018), the outcomes reported included, but were not limited to, science content. Other reported outcomes included views of the nature of science, scientific literacy, practical and experimental skills, use of technology, team working, attitudes towards science, creativity, motivation and self-efficacy. Again, the review noted that reported outcomes related to project providers' intentions rather than the outcomes that teachers intend or desire for their students. In the present study, our interest is in teachers' intentions, approaches and perspectives.

Despite the body of evidence suggesting a range of positive outcomes for students, minimally-guided instruction, as inquiry learning is sometimes characterised, has been criticised as likely to be ineffective because of a perceived ill-fit with what is known about working memory, and criticisms of the assumption that knowledge is best acquired through experiences of disciplinary procedures (Kirschner et al., 2006). Kirschner et al., however, conflate a number of approaches that are open or guided to different degrees (Hmelo-Silver, Duncan and Chinn, 2006), and do not fully acknowledge that inquiry learning is not synonymous with minimal guidance, and indeed can be highly guided. One of the challenges associated with assessing claims about effectiveness is clarity about what knowledge can reasonably be expected to be gained through open-ended investigations, and assessing the effectiveness of approaches on this basis. To make a fair assessment of the outcomes of open-ended investigation, it is important to understand teachers' beliefs and practices.

Teachers' beliefs and practices

Evidence suggests that teachers' beliefs influence their teaching practices and that these beliefs are gained from their own school experiences as well their understanding about how scientific knowledge is constructed, how it should be taught (Pajares, 1992) and by school culture (Wallace & Kang, 2004). Tsai (2002) classified science teachers' beliefs as 'traditional' (where science teaching is seen as a process of knowledge transfer from teacher to students), 'process' (with science teaching focused on processes of science, or problem solving procedures) or 'constructivist' (science teaching is seen as enabling students to construct their own knowledge) and found that more than half of Taiwanese science teachers had traditional beliefs. Tsai argues that there is an interplay between beliefs about science, science teaching and science learning and that to change science teaching (e.g. in favour of open-ended investigation), it may be necessary to change teachers' beliefs. Similarly, according to Mansour (2008), "teachers' beliefs about learning science refer to their conceptions of the process of learning science, what behaviours and mental activities are involved on the part of the learner, and what constitutes appropriate and prototypical learning activities." (p. 28). Wallace and Kang (2004) note that actions represent one aspect of a teacher's beliefs, and argue that they should not be considered as separate.

Johnson (2009) found that middle school teachers' beliefs had an impact on their willingness to use inquiry in their science teaching, Wallace and Kang (2004) found that teachers' beliefs about learning in science were linked to their use of inquiry and Bencze, Bowen and Alsop (2005) found associations between teachers' views of the nature of science and their tendencies to include open-ended investigations in their teaching repertoires. This group of studies highlight the need to work with teachers to find out what they believe is important. It has been found that reflection on beliefs and practices can be used to bring about changes in professional practice (Cochran-Smith & Lytle, 1999). Any attempt to change practices should consider how proposed practices correspond to teacher's beliefs.

Nevertheless, constraints that impact on inquiry-based instruction have been identified, even where teachers' beliefs are consistent with the use of open-ended investigation. These include teachers' prior training (e.g. in relation to the extent to which they have gained a practical understanding of inquiry instruction), beliefs about their students (e.g. teachers who believe that their students are not capable of doing inquiry are unlikely to try it with specific groups), their understanding of nature of science and scientific inquiry, content knowledge, pedagogical content knowledge, and concerns about management and students (Roehrig & Luft, 2007). Roehrig and Luft recognise that these constraints work collectively to influence instruction. In this study, we focus on the beliefs and practices of teachers who offer opportunities for students to engage in open-ended investigation, suggesting that they have negotiated these challenges to some extent.

Research questions

Studies of teachers' roles in open-ended investigation have included surveys of teachers' views of the incorporation of such work into the curriculum (Kennedy, 2014), and the impact of teacher scaffolding of open-ended work on student learning (van Uum, Verhoeff & Peeters, 2017). Whilst the aims of organizations promoting open-ended investigative work have been reported (Bennett et al., 2018), and outcomes of interest to researchers investigated (Minner et al., 2010), there has been little focus on teachers' aims for student learning through open-ended investigation, their approaches to such work, and the strategies they use to bring learning about. Given the reported benefits of open-ended investigation, which conflict with the scarcity of practice in England, we were interested in the overarching question: what are high school teachers' learning intentions, approaches and perspectives in relation to open-ended investigation? This is important to know because the knowledge gained from answering this question can be used to bridge the gap between the reported benefits of open-ended investigation and the scarcity of practice at the post-16 stage. The present research addresses the following sub-questions:

(1) What key ideas do teachers intend students to learn through open-ended investigative work in science at the upper high-school level?

(2) What teaching approaches do teachers use to achieve learning about these key ideas?

(3) How do teachers perceive and approach open-ended investigative work at the upper high-school level?

(4) How do teachers perceive their role in teaching open-ended investigative work in science?

It is not our intention to provide a picture representative of the teaching of such work across England; rather we provide an indication of some of the various ways in which investigation can be approached and is perceived. The findings are expected to be useful for informing teacher professional development and reflection, and for those developing curricula involving investigative work.

Methodology: phenomenography

Phenomenography is the empirical study of '*the qualitatively different ways in which people understand a particular phenomenon or an aspect of the world around them*' (Marton & Pong, 2005, p. 335), in this case, teaching open-ended investigation at the post-16 (pre-university) level. Although in different institutions, providing different types of experience, these teachers share interest in a common educational approach: open-ended investigation with post-16 students. Phenomenography results in different ways of understanding represented as categories of description. These categories are then analysed relationally to form an '*outcome space*' (Marton & Pong, 2005, p.335). Phenomenography focuses not on the phenomenon (in this case, open-ended investigation) but on the variation in people's (here, teachers') ways of understanding it (Larsson & Holmstrom, 2007). In this study, our aim is to characterise some of the ways in which open-ended project work can be perceived by teachers, and how this relates to their intended learning outcomes, with a focus on the variation between individuals. Phenomenographic approaches have been used to describe how students approach (Burrows et al., 2017) or perceive (Domin, 2007) learning, how academics approach teaching (Trigwell, Prosser & Waterhouse, 1999), and with the aim of influencing how teaching and learning experiences in science can be organised (McDonnell, 2016).

Phenomenography is appropriate for achieving these aims as it assumes that there is '*no right or wrong in the phenomenon being investigated*' (Burrows, Nowak & Mooring, 2017, p.813), but rather that it is the experiences based on relationships between (here) teachers and the world that matter. Our focus is upon exploring the different ways in which teachers conceptualise and approach open-ended investigations, rather than attempting to objectively describe experiences or the effectiveness of any particular approaches. This approach makes it possible to understand which learning outcomes are prioritised, and therefore which teaching repertoires are most appropriate to draw upon to achieve these intended outcomes.

Institutional ethical approval was granted and participants voluntarily gave their informed consent to participate. A two-stage process was used to collect data: a screening questionnaire followed by interviews.

Sampling

As students of A Level in England are no longer required to undertake open-ended investigative work at A Level in England, and no collective association of teachers to which a sampling frame could be applied, sampling was opportunistic. Teacher participants were identified using existing professional networks and mailing lists, and by searching ASE (Association for Science Education) articles and conference proceedings for teachers' reports of open-ended investigation from 2008-2018. A link to an electronic screening survey was distributed. The questionnaire was used to ensure we were speaking to teachers who were conducting open-ended work (defined by us as investigative work in which students are not provided with one or more of the following characteristics: problem or question, theory or background, procedures or design, analysis of results, communication of results and conclusions), and to find out what teachers intended students to learn from such work. Only responses from those who were doing open-ended work were included in the dataset, their questionnaire responses analysed, and an invitation to interview issued. A total of 17 responses from teachers were received, and those responses that corresponded to open-ended investigative work through their responses to the questionnaire (n=13) were analysed, and the teachers invited to take part in follow-up interviews. All but one teacher responded and accepted the invitation to interview. We stopped recruiting teachers for the study when no new approaches emerged from the data.

Participants

We did not collect background data during the screening stage: only from teachers who participated in interviews. A total of 12 teachers were interviewed. All participants had taught for longer than five years, and six for over 15 years. The teachers worked across biology (n=6), chemistry (n=4) and physics (n=2) and were teaching a range of post-16 programmes. A Level programmes were the most commonly taught. Most taught within their specialism. Three teachers worked in colleges and nine in schools, all in the state sector, teaching the 16-19 age range. Three schools operated academic selection policies. All institutions had an Ofsted rating[1] of 'Good' or 'Outstanding.' Most schools and colleges (n=10) in which the teachers were working are found in the least deprived neighbourhoods. One institution is based in a neighbourhood in the most deprived decile. This raises questions over which young people can access opportunities for open-ended investigative work.

Identifying intended learning outcomes

The short electronic questionnaire was used to identify intended learning outcomes for open-ended investigation. The questionnaire contained questions on intended learning outcomes: *What concepts or ideas is it important for students to know in order to do successful open-ended investigative work?* and *What do you intend students to learn through open-ended investigative work?* and five questions to determine the level of inquiry of the investigative

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[1] Ofsted (the Office for Standards in Education, Children's Services and Skills) inspects schools, colleges and other institutions. All state-funded schools are required to be inspected by Ofsted. The possible outcomes of an inspection are outstanding, good, requires improvement and inadequate.

work offered, drawing on the rubric developed by Buck et al. (2008). Following screening, only responses that indicated that students were not provided with one or more of the following six characteristics were included in the analysis: problem or question, theory or background, procedures or design, analysis of results, communication of results and conclusions. Out of a total of 15 teacher responses; 2 were excluded because they did not pertain to open-ended investigation, and one did not respond to the invitation to interview. A total of 13 questionnaire responses were included in the study and the teachers invited to interview. A total of 12 teachers responded and took part in interviews.

The responses to the two questions noted above were analysed to identify the intended learning outcomes teachers have for open-ended investigative work. Three authors independently read the responses, identified salient ideas and labelled these with codes. The three authors then compared the resulting codes, and through discussion arrived at a set of 'key ideas' which they felt described the data set. Our approach was informed by the process used in research to identify pedagogical content knowledge, which involves the identification of key ideas central to the teaching of particular topics (Loughran, Berry & Mulhall, 2012). Associated with each 'key idea' was a set of intended learning outcomes identified by teachers in the screening questionnaire.

Exploring approaches and perspectives

In common with previous phenomenographic studies in science education (Burrows, Nowack & Mooring, 2017; Domin, 2007), in-depth semi-structured interviews were used to collect data relating to teachers' approaches and perspectives. Teachers were invited to interview if they (i) conducted open-ended investigations with post-16 students; and (ii) worked in a state school or college.

A common guide was used for all interviews. Teachers were asked about how they organised investigative work, what they did to bring about learning of one or more of the key ideas identified from the questionnaire, and how teachers practically dealt open-ended investigative work in their institutional context. Teachers were asked to give concrete examples to avoid superficial descriptions, and to share how they understand open-ended investigative work (Larsson & Holmstrom, 2007). The nature of the investigative projects, along with practical barriers and enablers is reported elsewhere (Authors, 2019): the focus in this article is on learning intentions, approaches and perspectives. The interview guide drew on questions developed by Loughran, Berry and Mulhall, (2012) to explore how teachers structured learning of the key ideas. Our data is based on teachers' experiences and perspectives rather than particular observations made by the research team. Doing so allowed the identification of a number of qualitatively different ways that it is possible for participants to perceive teaching open-ended investigative work.

Interviews were recorded, transcribed and then analysed independently by two researchers using NVivo 12. In the first round of coding, any teaching repertoires mentioned were labelled with one or more of our identified 'key ideas', in order to identify the strategies used to support the learning of each key idea. The resulting codings were compared and discrepancies resolved through discussion.

Following this, a phenomenographical lens was applied to the data. In common with Larsson and Holmström (2007), each transcript was read and the interviews marked by two researchers where each of the third or fourth research question had been addressed. The transcripts were then examined by the same two researchers, who made notes on the focus of the teacher's attention, and how they described this in relation to open-ended investigative work. Through discussion between the two researchers, the teachers' descriptions of their approaches were grouped into categories. These were then assigned names that described their content by two of the research team.

Finally, each teacher was associated with the categories that corresponded to their responses, and associations between different categories were mapped to create an outcome space (a diagrammatic representation of connections between the different ways of perceiving open-ended investigation). These include hierarchies (Laurillard, 1993) and developmental progressions (Burrows, Nowack & Mooring, 2017). Associations between categories were identified in this study using a planar representation to show the connections between different perspectives.

Results

The findings are presented in two parts. In the first, intended learning outcomes that teachers have for open-ended investigative work are identified, along with associated teaching strategies. In the second part, ideal-typical approaches to open-ended investigations are identified and related to the learning of 'key ideas' in open-ended investigation. All teachers were involved in distinctive open-ended project work with their students.

Intended learning through open-ended investigations and associated teaching repertoires

Five 'key ideas' from the 13 questionnaire responses were identified: state of the field, real science, data handling, iteration and research design. In addition to these five ideas, teachers identified outcomes not related to learning such as meeting the aims of the curriculum and developing confidence and self-esteem. In interviews, teachers were asked to explain what they did in order to promote learning in each of the key ideas. Teaching repertoires were compiled according to key ideas and are presented in Tables 1 – 5.

Table 1 presents descriptions of teachers' repertoires for teaching state of the field as described during the interviews. This idea concerns learning about how (discipline specific) scientific knowledge is created, how to search, review and evaluate scientific research literature and how students' own work can contribute to a field.

[Table 1 near here]

Table 2 presents teachers' repertoires for teaching research design. Research design pertains to the students' decisions about methods to be used to answer a research question, including experimental design and data collection decisions, how to analyse data, equipment choices, safety awareness (including risk assessment) and consideration of ethical issues.

[Table 2 near here]

Table 3 presents teachers' repertoires for teaching iteration. Iteration in this context was identified as the non-linear repetitive and recursive process that links data collection and analysis. It is during iteration when students might test and develop their planned procedures, pilot data collection, and notice and respond to unexpected results.

[Table 3 near here]

Teachers' repertoires for teaching data handling are presented in Table 4. This refers to aspects of data collection, analysis and interpretation. This includes decision-making about the acceptability, adequacy and presentation of data, and interpretation and evaluation of results and associated claims. It also includes learning relating to statistical and graphical analysis.

[Table 4 near here]

Table 5 presents teachers' repertoires for teaching 'real science'. 'Real science' here relates to open-ended investigative work as an opportunity to conduct work similar to that of professional scientists. Whilst the other key ideas contribute to 'real science', the repertoires included here relate to learning the sociology of science - what scientists do and how.

[Table 5 near here]

These repertoires document the various strategies that teachers used to promote learning through open-ended investigation. Whilst the dataset does not allow us to comment on the effectiveness or otherwise of these approaches, it does provide five clear objectives for open-ended investigation, along with a range of methods used to promote learning. The repertoires and associated intended learning outcomes are likely to be of interest to those involved in developing curricula, resources and assessments relating to open-ended investigation and as a source of professional development for teachers who do, or are considering doing, open-ended investigations with their students for the post-16 age group.

Ways of perceiving open-ended investigative work

Analysis of interview transcripts found six distinct ways that teachers perceive open-ended investigative work. These perspectives encompass views of the nature and purposes of the work, and of the teacher's role. The categories of description have been labelled: *teacher-scientist*, *teacher-inquirer*, *instrumentalist*, *scaffolder*, *independence-builder*, and *personal developer*. Each corresponds to an emphasis on one or two of the key ideas identified from the questionnaire data (Table 6). In common with other phenomenographic studies (cf. Burrows et al., 2017) individual participants expressed their views among several categories of description (see Figure 1, at the end of the results section). Quotes are attributed to individual teachers using pseudonyms.

[Table 6 near here]

The teacher-scientist perspective

The teacher-scientist perspective focuses on a narrow scientific field defined by the teacher, with the emphasis on the teacher's interests. The projects carried out by teacher-scientists were typically long-lived, involving more than one cohort of students. External relations and collaborations are important in this perspective - with funders, scientists in industry and academia. Given the degree of specialism, they tended to take place outside curriculum time.

For teacher-scientists, learning tended to focus on the state of the field, and often extended to contributing to the field through presentations or contributions to journal articles. The teacher-scientist perspective involved introducing students to a specific topic and/or specific methods by which the question could be investigated. It was often less open-ended for students (structured or guided rather than open or authentic) because the teacher was deciding the research direction and participating in the research themselves in collaboration with external contacts, often over an extended (several years) period of time, when research started with one group of students would be continued with another. This type of work tended to involve a briefing of some description. As a biology teacher described:

> Initially they were given a brief, which was a little bit about [the topic] and a little bit about the research study that we were basing our study on...so they had to look things up and do some research on that as well. (William)

The teacher-scientist perspective views open-ended investigations as helping students to build links between different curriculum areas and to apply their knowledge to contemporary problems.

> The students need to understand the entire background to what they're doing so it's set within a context. And if it's set within a context which they'll understand and they can relate to the real world - as opposed to the curricular world - they can then start making lots and lots of links and bridging exercises between other things and that's where the creativity comes in because...then it strengthens their understanding and application of what it is that they're doing. (Alan)

The teacher-scientists were motivated to do science themselves, not only provide opportunities for students. They thrived on doing science and described it as a "necessity"

(Mike) for them to remain in teaching. Teachers who had this perspective took an approach that was responsive to the project, and which involved learning without limits, for example:

> So, we don't even look at the traditional boundaries of education; we just go, 'This is interesting; what happens if we do this?' (Alan).

This contrasted with the views and experiences of some teachers in the study, who saw what you can do in a classroom as quite limited:

> I don't know what they would be able to contribute that's not already out there. How they would go about doing it is beyond me, how I would be able to support them to do that is kind of beyond me. I honestly don't see the kids being adventurous enough to try something like that. (Karen)

The teacher-inquirer perspective

The teacher-inquirer perspective focuses on science as a way of finding out about the world and is driven by curiosity about the world, not limited to a specific topic, and often investigating areas that do not typically receive much attention in the classroom. In contrast to the teacher-scientist, the teacher-inquirer perspective did not involve commitment to a specific research project, but rather interests and approaches shifted according to students' interests and needs and emerging opportunities in science education, with the teacher adopting a more facilitative rather than participatory role.

> I tend to sort of think, well, science is science whatever the context…that's the key thing with these sort of open ended projects, it's not to try and force them down the teacher's favourite route. (David)

The teacher-inquirer approach involved teachers in an enabling role, for example creating time for students to follow their ideas through, or making connections with scientists. For the teacher-inquirer, external partners were involved on an ad-hoc basis, and tended to be approached based on students' interests and needs.

> It was up to them to decide when they met and to fix up meetings with the mentor at the university. But then, I was here in college and I met them at lunchtimes or free periods, just to give them a helping hand. (Stephen)

In the teacher-inquirer approach there is a focus on students' interests and 'real science' is the big idea being addressed. Often neither teachers nor students knew the answer to the question being investigated:

> It's getting them used to the idea during the A Levels that we don't know all the answers and there's still plenty of science out there for them to do. (David).

The teacher-inquirer perspective rejects limits by curriculum, age or institution:

> At no point do you say, "Oh no, you can't do that; you're not old enough." You just say, "No, crack on. If you've got to that stage that you can solve this problem you get to that problem and we'll then take it to what you need to do next until you reach your next problem, and you solve the problem", and they keep going by solving the problems. (Alan)

This perspective involved much one-to-one discussion about emergent issues as a teaching approach, pointing out where students' experiences corresponded with those that were common in 'real science', paying attention as much to the way research works as the topic under investigation:

> I think some students were a little bit disappointed that it hadn't shown an effect, but I said, "Actually, that's the majority of science" (laughter)…And I've read articles about how this is a great issue because people feel under pressure to get results and to publish things that work and show difference…I think it's getting the students to think critically…that's why I think it is important that you don't know what it is the outcome's going to be. (William)

In the teacher-inquirer perspective, teachers were typically learning in tandem with the students:

> Because I've usually done these projects in collaboration with somebody else, that I've found that a great learning opportunity as well. (William)

Whilst the teacher-inquirer perspective has much in common with the teacher-scientist approach, the investigations are much more student-originated and student-driven with teachers taking a more supervisory and facilitatory than participatory role. There is commitment to science and scientific method, but not to a single field or topic. The products of investigation were more varied, including presentations, reports, posters and videos to a broad audience, with less focus on discipline specific outputs and conference presentations.

The instrumentalist perspective

The instrumentalist perspective positions open-ended investigation as a tool for achieving something else (e.g. assessment, award, a good grade on a qualification, evidence for a university application form). This approach is often driven by awards or recognition, primarily for the students, to either drive or justify the work.

Whilst students have some freedom to pursue their interests, the instrumentalist approach requires projects to be self-contained and feasible within a given timeframe, with the degree of open-ness often dictated by examination board requirements. Teachers seeing open-ended investigations instrumentally tended to be driven by concerns about design and data, and therefore the focus on learning for these teachers relates to research design and data handling. For example,

> Research design, partly the same reasons as data handling; it helps them with their course. (Anna)

For teachers with instrumental perspectives, open-ended investigation was seen as a way of filling time at a difficult part of term for teaching subject content.

> There are some pragmatic reasons why that's a good time to do it, because if you try and deliver content at that time, people are out on trips, they're out on exams, they're doing all sorts of other stuff and so many missed lessons, that you cannot be sure that you've covered enough with enough people to make it worthwhile delivering content. So, it's better to do an investigation and then they can basically work through it at their own pace. (Christopher)

Teachers adopting an instrumentalist perspective tended to be concerned with what students were expected to do to meet the requirements of a specification or other external criteria.

> The first part of the assignment – and these are standardised assignments that are written by [the awarding body], they are not ones that we come up with, but they are generic – they have got to research an area, find protocols, a number of protocols and then put forward their proposal and that will get marked. (Emily)

Some teachers felt the instrumentalist approach originating from the students.

> The problem is not necessarily doing it, it's getting the kids to buy into doing it when their head is, "I need to know exactly what I need to know for my exam, teach me what I need to know for my exam. I don't care if I know how to apply it, just teach me what I need to know for my exam". (Karen)

Instrumentalist perspectives include the idea that open-ended investigation helps students to prepare for life beyond school, e.g. in a competitive academic or job market. Teachers noted that skills gained from open-ended investigation would look good on an application form, CV or professional social networking site:

> It's something that will help them in their personal statement, in their UCAS[2] application and everything like that. (Karen)

This approach was often associated with the belief that open-ended investigative work impacts positively on attainment.

> These are the students for us who would normally be getting grade C, grade D and to actually give them the chance of collecting and handling their own data and making sense of it we felt the [open-ended investigation] would support the main academic A Levels. (David)

The scaffolder perspective

The scaffolder perspective can be considered the structured interaction between teacher and student which helps the student reach their goal. The scaffolder approach to open-ended investigation focuses on progression in specific skills, and is tailored to individual student needs. Learning tends to focus on iteration and mastery of practical techniques in science.

The scaffolder perspective is concerned with the progress students can make over time, and involves creating opportunities for students to become increasingly independent, e.g. in their ability to select equipment or methods appropriate for the task. Sisi describes her approach to gradually withdrawing support:

> I try to scaffold the process...I am just trying to get them to remember, say what sort of equipment. And, then we would maybe do the experiment, I would give them just the equipment that they would need for the experiment and then ask them why you would use the thermometer, or why you are using a spatula, and then give them the problem. We would probably talk to the group in terms of how we would set up this equipment to solve that problem, thinking about what each is used for, and then they would then do the experiment. I would like to see over time, that they are given lots of equipment and then some that they

[2] University and Colleges Admissions Service, the system used for university applications in England

> wouldn't need for the experiment, and then pick out which one is going to be the one that we are going to use. (Sisi)

The scaffolder approach typically involved questioning to link previous experience with investigative work. Below, Stephen gives an example.

> We would get them to refer back to previous experiments that we'd designed, particularly the results of the investigations. We'd say, you know, "Well, when we've done a rates practical, what do we do with the data? How many data points did we need? When we wanted to plot a graph, how many data points did we need? And get them to think about…and then they would design an experiment. (Stephen)

The scaffolder approach requires time to be built in for development and testing to allow iteration before students start an open-ended investigation. This includes gradually introducing practical, mathematical and statistical skills throughout the course that students then apply in investigative work.

> We give them a chance to say, 'Does it work? Do you get data from doing this?' And quite often it doesn't go how they expect or they need to refine the method. So there's that aspect that they get to do it again. And sometimes their equipment isn't right, sometimes the results are a little bit strange and they get a chance to explain the results before they do the real thing...And then sometimes if they haven't got the right sort of data, or enough data, we'll allow them extra time to try and work out why it is that things haven't gone the way that they should have done. (John)

There were varying degrees of scaffolding employed by teachers, most typically questions specific to students and their projects during the most challenging steps, but ranging to teaching that scaffolded decision-making about procedures, equipment and data.

The independence-builder perspective

In contrast to the scaffolder, the independence-builder perspective concentrates on developing students' ability to work independently, with minimal intervention in science - although all teachers who shared practices corresponding to this perspective talked about asking questions and supporting students in a responsive way, not just leaving them to their own devices. That said, this perspective gives value to providing students with the space and time to take risks and make mistakes.

> They'd go, "Oh, that didn't work", and then they would backtrack; and they were doing the exploring part, the play part, the creative part. But there was no risk to it; they didn't get it wrong; they didn't fail; they just went down a blind alley and they realised themselves at some point that maybe that wasn't a good idea or there were certain limitations to the idea and then they could backtrack. (Alan)

Intended learning tended to focus on research design and iteration. Teachers working with this perspective took different approaches to supporting independence ranging from freedom over the topic and question, often with encouragement to use something of interest in their own lives, to front-loading teaching about a narrow concept or topic area so that students had the conceptual knowledge needed to ask questions, before designing their own investigation relating to the concept or topic taught. Contrast:

> It's supposed to be a piece of original research so what it can't be is looking up on the internet and textbooks and whatever else and just reporting what somebody else has found so they're having to do quite a lot of finding out for themselves. (David).

With:

> It's more than just decisions about experimental design; it's about understanding the context of the question and becoming an expert before you ask a question…you can't ask a good question until you know what question to ask. I don't give them a huge amount of autonomy, I give them effectively a research question area and then it's up to them to work out how to proceed with that...That takes less than a lesson to go through the basics and then I ask them to find out what experiments to be done and take it from there. (Christopher)

For teachers with this perception of open-ended investigation, it was important for students to learn the need for iteration, whether in designing and building equipment or collecting sufficient reliable data. For this perspective, process knowledge was prioritised over conceptual knowledge and teachers wanted students to learn how science works through experience.

The personal developer perspective

The focus of the personal developer perspective is on students' holistic development, for example in terms of resilience and confidence. In this perspective, learning tends to focus on real science and iteration, with the perception that by 'doing science' and experiencing difficulty and failure, the students will develop as people, For example:

> It gives the kids more confidence in looking at something they've not seen before. I think that's why our results are good. (Mike)

> I think just for them to build resilience and try and understand the scientific method properly, and although the theory can be applied, it doesn't necessarily mean that in practice you are going to get the same results. (Sisi)

Teachers with this perspective saw themselves as developing students' problem-solving skills.

> It is more about skills and being able to problem solve, because…whatever they are going to go into, it is more likely they are going to be given a problem or a project to work on, they are going to need to work out different methods to solve it. (Sisi)

The personal benefits were seen by teachers holding this perspective in both doing the investigation and in presenting findings.

> These students have not just presented to one person in a room; they've presented to an entire room of people who've come to listen from the chemical industry, from the local community, and they've stood at their posters and talked as they've been fired questions. Now that shows a lot of self-awareness, self-confidence. (Stephen)

For teachers seeing open-ended investigation as a way of developing students more broadly, presentations and other interactions were important in providing opportunities for students to develop confidence.

In summary, we have found six qualitatively different ways of perceiving open-ended investigation: the teacher-scientist perspective, the teacher-inquirer perspective, the instrumentalist perspective, the independence-builder perspective, the scaffolder perspective and the personal developer perspective. Phenomenographical studies typically describe an 'outcome space' to explain the connections between perspectives and how they relate to the phenomenon of interest. It does not make sense to organise the teacher perspectives identified in this study as a hierarchy or developmental progression because these different perspectives reflect different (not necessarily better or worse) orientations towards inquiry. Instead, here, we have made a planar representation (Figure 1) to show how the different perspectives on open-ended investigation are connected (or not) in order to draw out qualitative differences between the perspectives. Each teacher was associated with the perspectives they held, and a planar representation constructed (Figure 1) to show how the perspectives were shared amongst the individuals. A connection indicates that the two categories were associated with the same teacher. The following five findings were characteristic of the outcome space. Figure 1 shows that all teachers held more than one perspective.

[Figure 1 near here]

(1) No connections existed between the scaffolder and the independence builder perspectives. These are opposing approaches, with one valuing heavily scaffolding of investigative work, and the other giving students free rein to work independently. The balance between scaffolding and independence often depended on the type of project, with health and safety considerations a determinant of the scope for independence. Investigations requiring manipulation of equipment and chemicals typically required more scaffolding.

(2) The teacher-scientist perspective did not have any connections with the independence-builder perspective, perhaps because the former is more technically specialised and teacher-driven, with less scope for independent work.

(3) The teacher-scientist and instrumentalist perspectives did not connect. In the former, the teachers' interest in science was driving the investigation rather than value linked to a qualification.

(4) The personal developer and independence-builder perspectives did not connect. There was greater emphasis on scientific independence as an aim in the independence-builder perspective, rather than independence leading to greater confidence, resilience and other aspects of personal development.

(5) The independence-builder perspective had fewest connections, linking only with the teacher-enquirer and instrumentalist perspectives. These connections occurred in two situations: when there was luxury of time, e.g. through timetabling, for students to take full ownership of their project; or when the project had few associated risks and was not conceptually complex.

What this means is that teachers have a range of ways of perceiving open-ended investigation. These are associated with prioritising different learning outcomes. Designers of open-ended investigation opportunities and providers of such projects might find it useful to communicate about their offer in different ways to encourage uptake. Professional developers might find these useful in identifying different ways they can connect with teachers' beliefs in relation to inquiry.

Discussion

The 'key ideas' and teaching repertoires identified in this study contribute to understanding of teachers' practical knowledge (van Driel, Beijaard & Verloop, 2001). The intended learning outcomes identified by teachers in this study correspond in part to those identified by Minner et al. (2010) as components of instruction (question, design, data, conclusion and communication). 'Design'/'research design' and 'data'/'data handling' are common to both studies. Understanding the state of the field was important to teachers in this study, and included as a component of 'question' in the study by Minner et al. (2010). In the present study, 'communication' was included in the idea relating to 'real' science – doing what scientists do, and the teachers in this study did not discuss 'conclusion' in depth. The absence of inclusion of 'conclusion' in responses from teachers in this study suggests that this component of instruction in open-ended investigation might warrant further support. The intended outcomes identified by teachers in this study were not reflected in outcomes reported in the research literature, nor were they inconsistent with outcomes such as confidence and self-efficacy (Moote, Williams & Sproule, 2013), attitudes to science (Welch, 2010), and views about the nature of science (Metin & Leblebicioglu, 2011). This finding provides a set of outcomes that can form the basis of research aiming to determine the impact of open-ended investigation on student learning which takes into account teachers' intentions.

We found that some of our perspectives corresponded to those identified in the existing literature. For example, the teacher-scientist perspective corresponds with the key characteristics of 'teacher scientists' identified by Rushton and Reiss (2019): that through scientific methods, they develop their own, and their students' research skills, supported by research partners, using contemporary research articles at the frontier of the field. Teacher scientists establish research networks and encourage students to share their findings with others in a range of contexts. Similarly, in relation to the instrumentalist perspective, Wellington (2001) defines instrumental approaches to science education as those that value education in terms of its extrinsic value for life, work or the economy. This was evident from the sample of teachers in the study, where open-ended investigation was often valued in relation to the qualification being studied, and in enabling students to access further study. The idea of scaffolding in science education is traced back to Wood, Bruner and Ross (1976). Scaffolds include probing students' ideas, providing hints or suggestions and giving approval (Bliss, Askey & Macrae, 1996). In their meta-analysis of effects of guidance on inquiry-based learning, Lazonder and Harmsen (2016) found support for the hypothesis that scaffolds and explanations yield larger effects on learning than other types of guidance during inquiry (such as process constraints and heuristics), although measures of learning varied between studies included in the meta-analysis and did not necessarily correspond to these teachers' intended learning outcomes. Not all perspectives were found as approaches in the literature;

perhaps owing to the limited (albeit growing) use of phenomenography and social identity approach in science education research.

Whilst there is some correspondence with individual perspectives with those found in the literature (such as the teacher-scientist), the six different ways of perceiving open-ended investigative work resulting from phenomenographic analysis of interviews with teachers contrasts with classification systems reported in the literature to date. For example, Reohrig and Luft (2007) identify 'inquiry', 'process-oriented' and 'traditional teachers', noting that their 'traditional teachers' did not allow their students to investigate their own questions, plan their own procedures, or draw their own conclusions. Similarly, Tsai classifies teacher beliefs as 'traditional', 'process' and 'constructivist,' but does not focus on inquiry, other than in relation to the types of teaching and learning strategy associated with these different beliefs. The differences are likely to be due to our exclusive focus on teachers who were involved in inquiry science at post-16, whereas other studies have explored teachers' perspectives more broadly, and included inquiry as one component of teaching.

Limitations

The limitations of this study are that the teachers included were experienced, in schools graded 'good' or 'outstanding', often in the least deprived areas in England. Teachers tended to teach within their specialism. These contextual factors may be important in enabling teachers to carry out open-ended investigations. Indeed, it has been found that students in more deprived areas of England are offered fewer opportunities for practical work (Hamlyn, Matthews & Shanahan, 2017). Teachers with less experience or with more challenging teaching demands (e.g. teaching out of specialism) are likely to face more barriers to doing open-ended investigative work and participating in research studies. It is important to consider the equity implications of this. The study does not discuss open-ended investigations in contexts beyond the classroom (e.g. in fieldwork or university outreach contexts).

Conclusions

In relation to research questions 1 and 2, through the questionnaire, this study has identified five key ideas that teachers associate with open-ended investigation, and a range of associated intended learning outcomes. The 'key ideas' represent a source of guidance for organizations promoting and offering such work, suggesting that it would be possible to increase the focus on learning of science practices, going beyond goals relating to engagement, enjoyment, motivation and conceptual development. The key ideas are also likely to be of use to curriculum developers and awarding bodies in reflecting on how to design and assess open-ended investigations. Further research is likely to focus on learning progressions for open-ended investigative work, focused on the key ideas identified here.

Through the interviews, we have described the intended learning outcomes associated with key ideas, and strategies that are used for bringing about learning in relation to 'real' science, research design, data handling, iteration and understanding of the state of the field. This is likely to be useful to teachers and teacher educators, as well as authors of materials to support the teaching of open-ended investigation. The team is currently developing these practical outputs into a professional development programme to be offered in England.

In relation to research questions 3 and 4, the interviews revealed six qualitatively different ways of perceiving open-ended investigative projects: the teacher-scientist perspective, the teacher-inquirer perspective, the instrumentalist perspective, the independence-builder perspective, the scaffolder perspective and the personal developer perspective. The perspectives identified in this study represent a tool for reflection and professional development for teachers, both for those intending to develop their practice in this area or to introduce this type of approach to their teaching for the first time. There is scope for further (observational) research to find out how these reported repertoires are enacted by teachers.

Acknowledgments: Identifying so included in the main document.

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Table 1. How teachers promote learning about the state of the field.

What do you intend students to learn?	**How do you bring about learning?**
Illustrative examples from questionnaire responses	**Teachers' repertoires**
The bigger picture of an aspect of science. *About current developments.* *To link theory to experiments.* *How to make a literature survey without getting overwhelmed.* *How to develop their own picture of the physics of the system under study.* *The concept of how knowledge is built and verified.* *To gain specialised knowledge in a particular research area and develop a better understanding of the connections between different sub-fields of research.*	• Work with local university to secure access to research literature. • Ask students to read and summarise research articles. • Invite visiting speakers to provide theoretical and methodological grounding. • Ask students to read review articles written by speakers. • Ask scientists to recommend key papers. • Establish a journal club. • Deconstruct a research article - analyse structure and content. • Teacher presents a summary of research in a field. • Require students to draw on a range of sources in presenting their findings. • Provide a reading list/journal articles for students for their project area. • Work with university or STEM ambassador on mentoring in area of interest. • Ask students to find abstracts, discuss and decide which paper(s) to read. • Subscribe to school journals, e.g. Chemistry Review. • Teach what referencing is and how to reference. • Ask students to present posters to summarise the state of the field • Publish research e.g. in Young Scientists Journal. • Organise flash talks with scientists on different topics. • Teacher links to resources from Google classroom.

Table 2. How teachers promote learning about research design.

What do you intend students to learn?	**How do you bring about learning?**
Illustrative examples from questionnaire responses	**Teachers' repertoires**
How to conduct an investigation from start to finish. *Planning and organising skills - how to manage time in the laboratory* *Question formation, literature review, experimental design.* *To transition from following worksheets absentmindedly to understanding why each step is included.* *To ask the right question, identify data needed to answer it, and identify a way to collect that data.* *How to estimate whether a process is feasible in reasonable time before starting.*	• Ask colleagues in other departments for advice on instrument design (e.g. for psychology projects) • Discuss information provided on generic risk assessments in relation to e.g. concentration. • Provide students access to CLEAPSS[1]. • Require students to complete a risk assessment. • Deconstruct techniques (e.g. titrations) via reflective discussion. • Discuss sources and sizes of errors. • Discuss the ethical dimensions of the study, e.g. research with animals. • Ask students to research methods online and in books, evaluating the quality of sources. • Encourage students to plan their data analysis at the same time as they design their study. • Tell students what they must consider when planning and adapting methods from other sources. • Encourage students to identify control, independent and dependent variables in their design.

[1] https://www.cleapss.org.uk is a subscription service which provides health and safety guidance to schools, including how to conduct practical work legally and safely.

Table 3. How teachers promote learning about iteration.

What do you intend students to learn?	**How do you bring about learning?**
Illustrative examples from questionnaire responses	**Teachers' repertoires**
Resilience when initial methods do not work. *The challenges and rewards of conducting their own independent research which might involve troubleshooting, unexpected results, results that open new areas to investigate.* *To evaluate and reflect on own work.* *To apply knowledge and techniques to problem solving.* *To accept that things often go wrong, and develop strategies to mitigate this.*	● Provide time for students to experience trial and error. ● Explain the importance of repetition to students. ● Explain the role of troubleshooting and problem solving in science, especially when students are experiencing frustration. ● Provide opportunities for students to experience challenges. ● Share research experiences with students. ● Give students time (a double period) just focused on testing their methods before the begin an investigation. ● Provide time for students to amend or repeat their methods.

Table 4. How teachers promote learning about data handling.

What do you intend students to learn?	**How do you bring about learning?**
Illustrative examples from questionnaire responses	**Teachers' repertoires**
How to collect and evaluate data. *Ability to reach conclusions and evaluate processes.* *Research, analytical, presentation and team-working skills.* *Enhance understanding of practical techniques, deepen analysis skills.* *Learn how to progress an investigation beyond an initial plan; to choose suitable graphs to plot to test relationships.* *To collect data accurately and ethically.* *To analyse and interpret data appropriately.* *To understand the conditions required for statistical tests and how to graph.*	• Compare data to be collected to other studies to determine novelty of study. • Ask questions about the sample size needed to carry out statistical analyses in advance of data collection. • Teach ways of presenting data. • Provide practise workbooks with problems on data analysis. • Model how to handle data. • Ask students what the data they will collect means. • Teach methods of data analysis (statistical) before planning the investigation. • Ssk students to identify appropriate tests to answer questions of their own data. • Create opportunities for the students to 'do' data handling. • Teach graph plotting.

Table 5. How teachers promote learning about 'real' science

What do you intend students to learn?	**How do you bring about learning?**
Illustrative examples from questionnaire responses	**Teachers' repertoires**
An understanding of real-life [practical] science. *To communicate ideas.* *To appreciate political, economic, social, technological, legal and environmental factors that impact use of scientific advances.* *That science research is often collaborative, with contributions from different disciplines.* *The joy of discovery.* *The process of using experiments and evidence to find something out.* *How to approach an open ended problem*	• Use contexts to help students to explain why investigation is important. • Provide opportunities for students to investigate across disciplinary boundaries. • Avoid direct teaching - give students experience of working independently on asking a question, designing a study, carrying it out and communicating findings. • Ask students to create a hypothesis and to explain why their data does or does not support it. • Create opportunities for students to collaborate within and beyond their institution - place in groups; connect with a research laboratory. • Teach methods and ask students to apply these to investigate questions that they are interested in. • Ask students to write their project up for publication. • Enable students to make poster and oral presentations at conferences. • Provide an unfamiliar context for investigation. • Ensure students do not know (and cannot easily find out) the answer to their research question. • Explain null findings and how publication works.

Table 6. Learning focus of different perspectives on open-ended investigation

Perspective	**Learning focus**
Teacher-scientist	State of the field
Teacher-inquirer	‘Real science’
Instrumentalist	Research design and data handling
Scaffolder	Iteration
Independence-builder	Research design and iteration
Personal developer	‘Real science’ and iteration

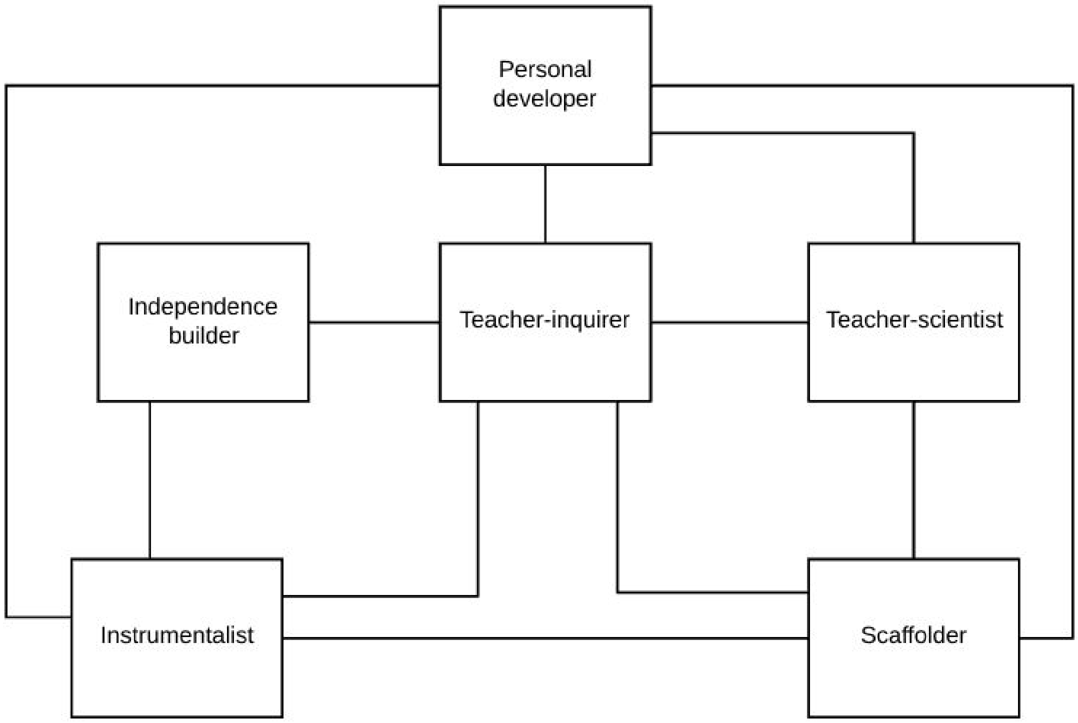

Figure 1. How perspectives towards open-ended investigation were shared across individual teachers. A line linking two perspectives indicates that they were both associated with one teacher.