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Design and Evaluation of Integrated Instructions in Secondary-Level Chemistry Practical Work

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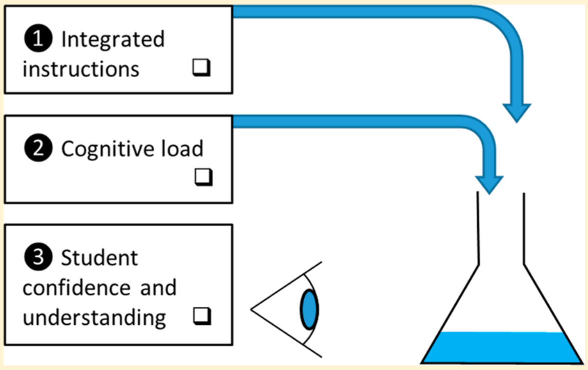
Supporting Information



ABSTRACT: Practical work in secondary-level chemistry laboratories involves a high cognitive load for students. In addition to reading and understanding instructions, students have to think about observations and the underlying chemical concepts, as well as deal with the noise and social interaction of a busy classroom. One form of extraneous cognitive load in practical instructions is the split-attention effect, whereby students have to continually switch their attention between apparatus diagrams and the written instructions. This article discusses the development, use, and evaluation of instructions that integrate apparatus diagrams with simplified textual and pictographic instructions. Four practical tasks were designed and evaluated: distillation of a crude oil substitute, properties of crude oil fractions, synthesis of copper sulfate, and pH and neutralization. Data were collected on students' and teacher's classroom experiences with the instructions, and students' learning was assessed after the practicals. In general, students found the practicals easy to complete, liked the clarity of the instructions, needed to ask few practical-related questions during the tasks, and mostly gave at least partially appropriate answers to postpractical questions on what they had observed and done. Integrated instructions provide a potentially useful method for reducing students' cognitive load and increasing their confidence and understanding during practical work.

KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Laboratory Instruction, Hands-On Learning/Manipulatives, Learning Theories, Microscale Lab, Applications of Chemistry*

INTRODUCTION

Practical work is a significant part of teaching chemistry to 11−18 year old students in the United Kingdom (U.K.). It provides a means to practice and understand the "essential aspects of knowledge, methods, process and uses of science"[1] in the classroom and is identified as prevalent in many of the schools that have been judged "outstanding" by the English schools regulator.[2] Practical work has many uses, including exemplifying scientific concepts, developing investigative and practical skills, motivating students,[3] and fulfilling exam specification requirements.[4]

Although the reasons teachers cite for using practical work have not changed significantly over time,[5−7] there are significant and persistent criticisms of much practical work.[8−11] Hofstein and Lunetta[8,9] identified no clear link between much of students' laboratory experience and what they are learning, with much practical work existing as cookbook style activities, with little link to wider scientific inquiry. The OECD[12] identified a negative association between inquiry-based instruction and scientific performance but a positive association with students' epistemic beliefs and expectation of working in science.

For practical work to play a meaningful role in students' education, careful design and integration of practical tasks within the wider scheme of learning is required,[11] with some requirement for direct instruction to help ensure effective progress and to minimize the development of misconceptions.[13] Projects to improve the quality and utility of practical work for student learning have met with some success, although effecting change proves difficult without sustained professional development and support for teachers in the classrooms.[14−17]

There are several reasons practical work can be ineffective. Johnstone and Wham[18] identified the high probability of students' working memories[19] becoming overloaded.[20] Students must pay attention to many factors, including dealing with apparatus, following written and verbal instructions, recalling and using skills and theory, and attending to the data from the experiment. Johnston and Wham made a useful comparison between lab sessions and theory sessions. In a lecture, a single defining principle is generally discussed and then elaborated on. By contrast, a lab session is "noisy", with students having to bring many factors together to elucidate a defining principle, and students can often be distracted by

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nonessential elements. Johnstone proposed strategies to improve the effectiveness of practical work, including prior development of skills and reduction of unnecessary "noise" through clear lab manuals and removal of noncritical steps.[21] In addition, chemistry is an intrinsically complex subject, and making connections between macroscopic observations and submicroscopic interpretations takes time and experience.[22]

The problem of overloaded working memory can be theorized using Cognitive Load Theory,[23] with cognitive load divided into

- intrinsic load, related to the inherent complexity of the task and the interactions between the elements of the task;
- extraneous load, related to how the task is presented and factors outside the task at hand; and
- germane load, related to how understanding develops and increases the complexity of the mental schema.

Many of the factors identified by Johnstone and others that lead to information overload[24] can be categorized as extraneous load (i.e., information that students must attend to that do not help with their developing understanding). How practical instructions are presented affects a student's extraneous load. Having to switch attention between two or more sources of information can increase extraneous load and is known as the "split-attention effect";[25−28] an example of this is when practical instructions are given as an apparatus diagram with a separate list of instructions.[29] For students with weaker literacy skills or those studying in a non-native language, this standard format of practical instructions can prove to be a barrier to engaging with the purpose of practical work.

One suggested technique for improving engagement with complex information is dual-coding.[30,31] Here, information is presented as a combination of visual representations and text. Haslam et al.[32] investigated this method with New Zealand secondary-school children in setting up and using simple electrical circuitry. They found that integrating the textual instructions with illustrations produced higher levels of performance in tasks and reduced time to completion and perceived cognitive load. Students using the integrated instructions, compared with those with written-only instructions, showed greater learning gains in written post-tests compared with pretests, had more favorable attitudes to laboratory work (although they were not necessarily more enthusiastic about it), and showed greater manipulative and organizational skills.

Dechsri et al.[33] studied the effect of integrated instructions with U.S. undergraduate chemistry students. Experimental groups carried out practical work using an integrated instructions approach, with control groups using only written instructions. Students in the experimental groups scored higher on achievement tests and had more favorable attitudes toward practical work afterward.

Davidowitz et al.[34] investigated the impact of undergraduate students converting written instructions into flow diagrams before using the diagrams in a laboratory setting. They found that students progressed through practicals faster with fewer failed experiments, and they had a better understanding of what they were doing. An aspect of this improvement may be down to the multiple exposures to the practical task, as well as to the use of the pictorial instructions. Such multiple exposures are a key aspect of other techniques recently investigated to improve practical work.[35]

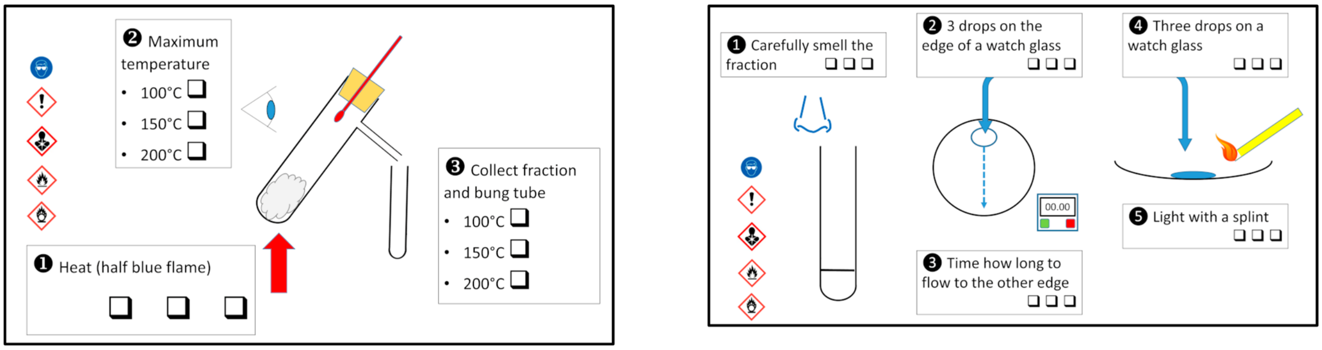
The ability of students to effectively visualize what they need to do from a set of written instructions may additionally be hindered by levels of cognitive development. Many students, even at age 16, have not progressed to the Piagetian formal operational stage, where they can deal with more abstract concepts.[36] The use of diagrams integrating pictorial representations of experimental apparatus and simple written instructions may help these students by providing a more concrete basis to work from.

■ DEVELOPMENT OF PRACTICAL SKILLS

A key focus of secondary science education is to allow students to engage in scientific inquiry with all concomitant aspects (hypothesis generation, method development, data collection and analysis, and so forth). To develop students' self-sufficiency and efficiency in carrying out an inquiry, they need opportunities to learn and practice using apparatus and techniques. This learning can be via isolated direct instruction on the apparatus and techniques or within the context of practicals focused on elucidating chemical concepts. For example, accurately measuring the volume of a liquid can be taught by providing a range of measuring devices (beakers, measuring cylinders, burets, etc.) and asking students to demonstrate their accurate use. Subsequently, this technique can be used in experiments such as measuring the rates of reactions, the synthesis of salts, and quantitative analysis via titration. As a second example, accurate manual handling of chemical substances is a key skill of a competent chemist and necessary for the accurate production of samples on which data collection relies. The opportunity to develop these skills can be taught in isolation, for example by asking a student to accurately weigh out a sample of solid, or in the context of an experiment based on reinforcing a chemical context, for example in a demonstration of the dissolution and precipitation of substances in droplets of water.[37]

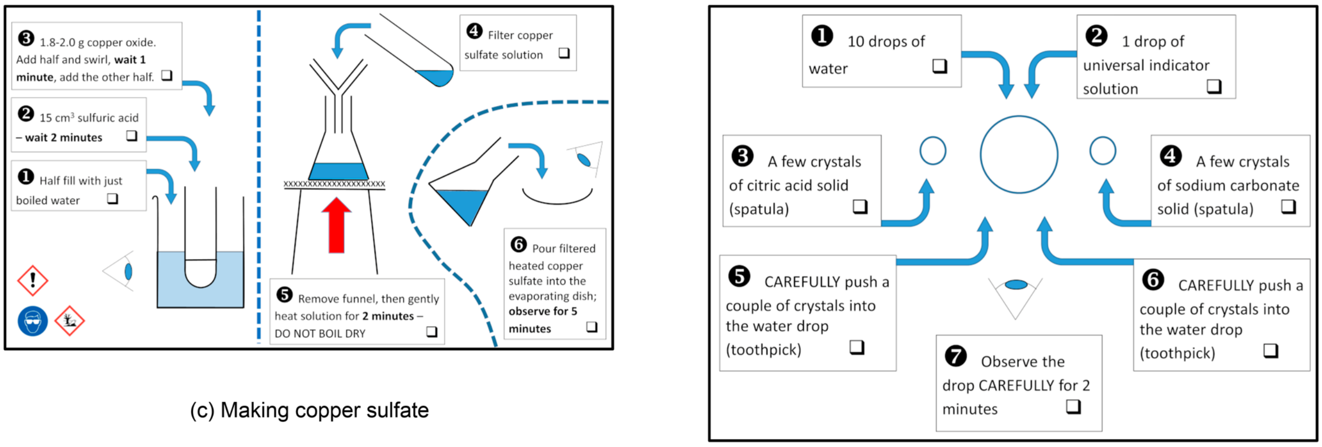
Overlaying the development of a comprehensive practical curriculum are the restraints placed on teachers by exam-board requirements and school-based resources. For example, under the current examination regime in England, 14−16 year old students studying for the General Certificate of Secondary Education (GCSE) Chemistry qualifications are required to complete a minimum of eight defined practical activities and to have experience with a range of apparatus and techniques. In the AQA Chemistry specification,[38] these "required practicals" range from the very specific, such as the "preparation of a pure, dry sample of a soluble salt from an insoluble oxide or carbonate, using a Bunsen burner to heat dilute acid and a water bath or electric heater to evaporate the solution" (Required Practical Activity 1), to the more inquiry-based, such as "investigate how changes in concentration affect the rates of reactions by a method involving measuring the volume of a gas produced and a method involving a change in colour or turbidity. This should be an investigation involving developing a hypothesis" (Required Practical Activity 5).

The preparation of a dry sample of a soluble salt involves a wide range of apparatus and techniques and likely involves a cookbook style instruction set. Despite the criticisms of learning-gains from such practical work, students completing the work should gain increased familiarity, confidence, and competence in the apparatus and techniques, and as such, should be better prepared for other future tasks using similar apparatus and techniques. In completing a rate of reaction investigation that includes hypothesis generation, students are



(a) Distillation of crude oil

(b) Properties of crude oil fractions



(c) Making copper sulfate

(d) pH and neutralization

Figure 1. Four integrated instructions for practical tasks. In each, simple apparatus diagrams and textual instructions are combined within one diagram. Each practical step is numbered, and tick-boxes are included to help students to keep track as they work through the practical. Multiple tick-boxes are included when a particular step is repeated multiple times (a,b). An eye pictogram is included where particularly careful observation is required (a,c,d).

required to attend to multiple aspects of the inquiry, including apparatus and technique, and prior experience with these should prove beneficial in helping students be less cognitively overloaded by the actual practical work. This is particularly important in, for example, GCSE "required practicals", where students are expected to be more investigative, and their main focus of attention should be on, for example, hypothesis generation and overall experimental design.

Regardless of the purpose of the practical task, from simple production of a standard observation to a full inquiry, reducing the cognitive load on the students during practical work should be beneficial in allowing them to focus on their manipulations and observations, rather than on difficulties in interpreting written instructions. Additionally, although work by others[25−28] indicates that extraneous load caused by split-attention is a common issue for students, additional benefit may be gained by those with weaker literacy skills or those studying in a non-native language. Reducing the number of words students have to read and making use of visual resources can be particularly helpful when teaching students for whom English is an additional language.[39]

■ DEVELOPMENT AND USE OF INTEGRATED INSTRUCTIONS

An early driver of the current development of integrated instructions was to improve student efficiency and independence in the short 45 min lessons available to the author. A significant amount of time can be wasted in a practical session with what Johnstone[24] called "thoughtless questions". Many of these are likely to be the product of students' overloaded working memory and hence are externalization of decision making to the teacher (e.g., "What do I do next?" and "What do I do with the test-tube?").

To give students a greater opportunity to focus their attention on the skills they are developing, integrated instructions provide a potential method for reducing extraneous cognitive load by minimizing the splitting of attention between a diagram and a list of instructions. Both Dechsri et al.[33] and Haslam et al.[32] have previously shown the effectiveness of integrated instruction in their contexts. Dechsri et al.[33] developed integrated instructions that took the written instruction and added an indicative illustration, including arrows to direct movement of materials and a timer to indicate measurement of time. Evidence was provided on the effectiveness of the instructions with U.S. first-year undergraduate students in a one-semester course. Haslam et al.[32]

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Table 1. Overview of What and How Students Investigate in Each Lab Practical

Practical	Description	Techniques Used (Apparatus Used)
Distillation of crude oil substitute[a]	Heating a crude oil substitute in a side arm boiling tube connected to a delivery tube to collect three fractions over predetermined temperature ranges	Handling hazardous materials Heating substances (Bunsen burner) Measuring temperatures (thermometer)
Properties of crude oil fractions	Observing odor and flammability and measuring the viscosity of the fractions	Handling hazardous materials Safe smelling of substances Measuring time (timer)
Making copper sulfate[b]	Synthesis of copper sulfate from copper oxide and sulfuric acid and purification of copper sulfate by evaporation and crystallization	Handling hazardous materials Measuring volume (measuring cylinder), mass (top pan balance), and time (timer) Heating substances (water bath) Separation techniques: filtration (funnel, filter paper), concentration (Bunsen burner, tripod, gauze, conical flask), and crystallization (evaporation dish) Handling hot glassware
pH and neutralization[c]	Observing the effects of neutralizing citric acid with sodium carbonate in a small drop of water	Manipulation of very small amounts of substances Close observation of a reaction

[a]See ref 41. [b]See ref 42. [c]See ref 43.

Table 2. Comparison of Time Needed by Students To Complete Each of the Four Practicals and Performance on Postpractical Assessment Items

					Appropriateness of Responses, %		
Practical	Student Participant Group	*N*	Mean ± SD of Completion Time, Min	Postpractical Assessment Items: Observation Type Items (O) and Purpose of Step or Equipment Type Items (P)	FA[a]	PA[b]	NA[c]
Distillation of crude oil substitute	Mid2	15	21 ± 2	A. Describe the change in temperature you observed as you heated the crude oil. (O)	64	36	0
				B. What observations did you make that showed distillation was occurring? (O)	18	73	9
				C. What was the purpose of the tube between the boiling tube and the collection test tube? (P)	36	64	0
Properties of crude oil fractions	Mid2	15	11 ± 2	A. Describe how the viscosity changed between the fractions. (O)	56	22	22
				B. Describe how the ease of setting light to the fractions changed between the fractions. (O)	44	12	44
				C. Describe how the odor changed between the fractions. (O)	0	100	0
Making copper sulfate	High1	24	22 ± 5	A. What observation(s) did you make that showed you a chemical reaction had occurred? (O)	72	28	0
				B. What was the purpose of step 5: Gently heating the solution for 2 min? (P)	25	13	62
				C. Describe the purpose of step 6: Pouring the solution into an evaporating dish. (P)	89	11	0
	Low1	12	21 ± 2	A. What observation(s) did you make that showed you a chemical reaction had occurred? (O)	44	56	0
				B. What was the purpose of step 5: Gently heating the solution for 2 min? (P)	33	56	11
				C. Describe the purpose of step 6: Pouring the solution into an evaporating dish. (P)	44	34	22
pH and neutralization	High1	24	13 ± 3	A. Describe the sequence of observations: What happened first, second, etc. (O)	63	37	0
				B. What observations did you make that solutions were formed? (O)	0	67	33
				C. What observations did you make that showed a neutralization had occurred? (O)	47	53	0
	Low1	12	12 ± 2	A. Describe the sequence of observations: What happened first, second, etc. (O)	14	86	0
				B. What observations did you make that solutions were formed? (O)	0	100	0
				C. What observations did you make that showed a neutralization had occurred? (O)	17	83	0

[a]Answer deemed fully appropriate. [b]Answer deemed partially appropriate. [c]Answer deemed not appropriate.

took a similar approach of diagrammatic illustrations of the apparatus, with numbered instruction steps pointing directly to where student interaction with equipment was required. Evidence was provided about the effectiveness of the instructions with secondary-school students in New Zealand. The present work takes cues from both of these studies, and develops integrated instructions further by minimizing text and providing further visual cueing for students. Evidence of the effectiveness of these instructions is discussed in the context of 14−16 year old students in an English school. The key features of the present integrated instructions are

- standard "cut-through" diagrams of apparatus showing relative positions and orientations (the apparatus are not labeled to reduce extraneous information, given that students learn these diagrams early in their secondary curriculum);
- numbered instructions arranged, where possible, in a clockwise or anticlockwise direction to minimize students having to "jump around" the instructions;
- use of clear arrows to direct action, minimizing the number of words required in the instructions (e.g., "**Place** 2 cm^3 **of** 0.1 M NaOH **in the test tube**" becomes "2 cm^3 0.1 M NaOH" with an arrow from the instruction box into the mouth of the test tube);
- use of check-boxes to allow students to track their progress through the practical, helping to ensure all steps are completed and minimizing the need to remember which step they are on; and
- use of pictograms to draw the students' attention, such as an eye to indicate exactly where observation should be made (e.g., the middle and top of a test tube during the thermal decomposition of ammonium chloride) and clocks and balances to indicate measurements to be made.

Initially, integrated instructions were being developed for a number of teaching groups on an ad hoc basis and anecdotally seemed to be proving useful for the students. It was hence decided to investigate the effectiveness in a more systematic way. Three teaching groups were identified in the author's teaching timetable, that covered a range of student attainments and from two year groups. Group "High1" was a mid/high attaining group in their first year of GCSE study; group "Low1" was a low attaining group in their first year of GCSE study; and "Mid2" was a low/mid attaining group in their second year of GCSE study. The practicals selected for development and investigation were chosen on the basis of upcoming activities in the departmental scheme of work. Subsequently, a wide range of practical activities have been developed in the integrated instructions style (see ref 40).

All instructions were created using simple shape drawing in Microsoft PowerPoint, and a set of templates have been created to allow rapid development of new instructions (see ref 40). Where time allowed, a colleague was asked to try out the practical following only the integrated instructions to see whether all the salient points had been captured.

Before introducing a new class to integrated instructions, time was spent discussing with the students why the instructions had been developed and their potential benefits, so the students understood why they were being used. During the practical session, students received a paper copy of the practical instructions (see the Supporting Information) to work from, and a copy was projected onto the class whiteboard for easy reference and discussion. The students were asked to annotate the instructions where they had questions during the practical work, and to tick the boxes to keep track of their progress. The practicals (Figure 1) covered a range of areas of chemistry and practical apparatus and techniques (Table 1).

To better understand the value of integrated instructions in the classroom for both students and teachers, a range of data were collected, including the questions students asked during the practical work, teacher's reflections on the practical work, students' written answers to postpractical questions, and students' ranking of their understanding and confidence during the practical work due to the integrated instructions. Further details of data collection and analysis are provided as Supporting Information.

■ STUDENTS' EXPERIENCES OF USING INTEGRATED INSTRUCTIONS

All students completed all of the practical tasks they were given within the 45 min lessons (Table 2). The number and types of questions they asked during practical work varied among the groups and the practical tasks. On average, there was one question asked by every two students across all the practicals, although this varied; in the "pH and neutralization" (High1) practical, no questions were asked at all, and in the "Making copper sulfate" (High1) practical, 23 questions were asked.

Most of the students' questions were answered by referring them back to the instructions, which seemed to lead to more self- and peer-correcting over time. Several incidences of students correcting their peers with comments such as, "Look at the sheet and do the next step," were heard.

For the questions where further guidance was required, the majority related to minor technical points, such as what to do with the funnel when the filtering was complete. The students generally did not tick off the boxes as they went along. In other practicals (not forming part of this work) where the same task was repeated multiple times, for example when carrying out rates of reaction experiments, students were more often seen ticking off boxes to keep track.

To assess student understanding of the observations made and techniques used, three postpractical questions were given. It is noted that there are other significant sources of learning during a practical beyond the instructions themselves, including the initial teacher demonstration of the task, learning from peers through observations, and students' own problem solving. Also, no data were collected regarding the prior knowledge of the students, nor was there any formal assessment of the validity of the questions in assessing the understanding of the students (see the Limitations section). However, the students' ability to answer these questions is indicative of the learning occurring during the practical and additionally provides useful practice for the students on the types of questions they answer in GCSE exams.

Student responses to the "Making copper sulfate" questions are discussed here to exemplify their responses; further analysis is provided as Supporting Information. All students gave at least partially appropriate responses to the question about the observations they made showing that a chemical reaction had occurred (e.g., "When we added the copper oxide (black) after swirling the solution, it turned light blue..."). Some incorrectly inferred that hydrogen was being produced (e.g., "... When we heated it, hydrogen gas produced (it bubbled)"). The purpose of heating the solution caused the most confusion, with fewer than half the students giving fully appropriate answers and most erroneously stating the purpose was to increase the rate of reaction (e.g., "To speed up the reaction"). The purpose of pouring into the evaporating dish was much better understood,

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with most students giving at least partially appropriate answers (e.g., "The basin was a larger surface area so it will evaporate faster to speed up crystallisation").

The majority of the students found the activities easy (see the Supporting Information). Two general themes were identified from their written comments about their understanding of and confidence in completing the practicals. They liked that they could "see" what the practical looked like (e.g., "... the pictures helped my confidence. I could visualise what I was doing") and the independence they felt in completing the practical (e.g., "It helped me do the practical without asking the teacher"). Although there is not necessarily a direct link between how easy a student finds a task and their confidence in completing the task, student motivation is an important aspect of student progress. If students find tasks too hard to complete, motivation can decrease, and progress can stall. Over the course of this study and subsequently, it was noted that once students were used to the integrated instructions, they were more willing to persist with practical work and complete the tasks with satisfactory outcomes. For example, the High1 group that the author continued to teach in their second year of GCSE study developed into a competent practical group; further practical tasks carried out using integrated instructions were completed efficiently, with all students achieving required observations and measurements in the limited lesson time. This allowed more lesson time to be devoted to nonpractical aspects of scientific inquiry, including hypothesis generation and data analysis and evaluation.

■ TEACHERS' REFLECTIONS ON USE OF THE METHOD

Any new teaching method will have an impact on the outcomes achieved by the students in a class, either positive or negative. The integrated instructions method partially grew out of a frustration in some students' apparent inability (or unwillingness) to follow "standard" written instructions for "standard" practicals. The postpractical notes (see the Supporting Information) were helpful in highlighting the perceived immediate benefits or otherwise of the integrated instructions. There was a noted general trend toward students working independently of their teacher, self- and peer-correcting, and supporting each other. In terms of classroom management and student progress, this is particularly important, as teachers need to maintain an overview of the whole laboratory for health and safety purposes and ensure students are remaining on task, rather than spending a large amount of time dealing with questions that students can have answered in other ways.

These and other integrated instructions have been shared both within and outside the author's faculty. The responses of other teachers have been positive, with some of the activities being substituted into our collective schemes of work. One faculty member, K. Nielsen, noted, "Students have shown an increased understanding of why each step is being performed and the layout and timings tend to allow for more fluid discussion than with traditional numbered lists... This has resulted in a significant increase in confidence and competence with experimental techniques and procedures." A teacher from another school (A. Robbins) developed his own integrated instructions based on the author's templates and noted, "They all completed the practical in a 2 hour lesson. They did make a few mistakes early but the more able could access without extra guidance after a demo."

■ LIMITATIONS

The present study was carried out as an action research study on the effectiveness of integrated instructions in practical work. Although positive effects have been noted here and more widely with other practicals not detailed here, there are clear limitations in the rigor possible in the current evaluation. No systematic data were collected on the effectiveness of "traditional" practical work or the students' opinions of the same. This disallows for a comparison of the relative effectiveness of integrated instructions against traditional instructions. In addition, the choice of practicals studied and the choice of groups of students used were limited by those available in the author's timetable. At present, therefore, the current work represents a presentation of a novel method for presenting practical instructions with evaluation of student success in completing these particular practical tasks.

A more rigorous comparison is possible in the future by using matched groups of students with one completing practical work with integrated instructions and one with traditional instructions. Enlisting other teachers with similar teaching groups is a possibility, although confounding variables may be introduced, such as other teachers' styles of teaching, relationships within the group, and differences in teaching laboratories, among others. It may be possible to use the same teaching group and the same teacher, which may minimize the effects of these factors. However, careful consideration would then need to be made of the relative conceptual difficulty of the different practical activities used and the increase in practical competence that the students would have achieved over the time between the two practical activities.

■ IMPLICATIONS

Despite these limitations, positive outcomes have been seen from this further development of integrated instructions from Dechsri et al.[33] and Haslam et al.[32] Students and other teachers have responded positively to the use of integrated instructions in their learning and teaching. Students are generally more confident in completing practical work, and their competence is increased in the laboratory. More time is now being spent on the wider aspects of scientific inquiry, developing students as better scientists through the course. Teachers now have access to a set of exemplar integrated instructions for GCSE Biology, Chemistry and Physics practicals and templates to work from in developing their own instructions (see ref 40).

As part of the students' wider practical curriculum, focused learning of particular skills before they are used within more complex inquiry activities is useful. Indeed, the model of internal practical assessment currently used in the English General Certificate of Education (followed by students after GCSE study) requires evidence of competence in a range of skills, apparatus, and techniques over the 2 year course.[44] Students need a wide range of skills to be considered competent chemists. Methods such as integrated instructions, which allow students to develop these skills, alongside methods for consistent internal assessment[45,46] are useful.

Integrated instructions provide a technique for delivering practical instructions that allow students to more closely focus on the apparatus and techniques involved and the measurements and observations they are making. Extraneous cognitive load, due to the splitting of attention between a diagram and a list of instructions in a traditional cookbook style practical, is reduced, and students are provided with a clear visual instruction set that provides them confidence in carrying out the practical tasks.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00194.

Further details regarding data collection and analysis (PDF, DOCX)

Integrated instruction sheets for the four practical tasks (PDF, DOCX)

Data collected from each of the four practical tasks (XLSX)

Proforma for collecting in-practical questions (PDF, DOCX)

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Notes

The author declares no competing financial interest.

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