A holistic framework for developing purposeful practical work

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A holistic framework for developing purposeful practical work
Naomi Hennah, Sophie Newton, and Michael K. Seery

Abstract

This work applies a cultural historical activity theory (CHAT) framework to understand how the outcome of a high school laboratory task may be positively influenced without making changes to the hands-on practical task itself. Informed by cognitivism, novel practical instruction videos that were based on the same video but had different audio content (“one video two voice overs”) have been developed to provide opportunities to prepare for the practical task procedure and then to reflect upon the task’s underlying concepts. We use the CHAT framework as a guide to change pupils’ lab roles and rules of engagement were made to structure student interaction and facilitate an equitable and cooperative learning environment. We demonstrate that students benefit from these interventions and achieve significantly higher attainment scores in GCSE chemistry examination practical-themed questions than those students who prepared for the practical task by watching either the novel videos or standard instructional videos during the lesson. In addition the students working in the scaffolded cooperative learning environment also perceived their confidence in relation to practical-related tasks at higher levels than those in other groups. This work contributes a novel approach to laboratory teaching by placing greater emphasis on dialogic processes as a tool accomplish a practical-based activity.

Introduction

Assessment of practical work

In England, the study of science is compulsory up to age 16, culminating in the General Certificate of Secondary Education (GCSE) examination, with the study of chemistry accounting for approximately one third of the science curriculum. The national curriculum sets out the programme of study and attainment targets for GCSE chemistry. Exam boards such as the Assessment and Qualification Alliance (AQA) build a specification identifying key skills, understanding, and knowledge that students are expected to have gained by the end of their course. The specification aims to balance “what works in the classroom and what can be accurately marked and graded” (AQA, 2014). The exams regulator, Office of Qualifications and Examinations Regulation (Ofqual), ensures that the specifications are fair and meet the national curriculum criteria.

The examination boards specify the apparatus and the techniques which 15 to 16-year-old learners’ must gain experience of, by completing a minimum number of 8 practical tasks. Students are not assessed
carrying out these activities, but they need to keep contemporaneous records, and schools must confirm to exam boards that they have enabled their students to do the full range of practical work. Fifteen percent of the GCSE chemistry examination marks are assigned to practical-themed questions that draw on students’ experience of doing practical work, their investigative skills, and their ability to apply this knowledge in novel contexts (Ofqual, 2015). Teachers can choose whether practical episodes are conducted by the students, or are teacher demonstrated, and may also choose to employ other teaching aids such as videos or simulations (Moore, Fairhurst, Correia, Harrison, & Bennett, 2020).

Schools in England are encouraged to include purposeful practical activities as part of the day-to-day teaching of learning. As “[a]ssessment operationalises outcomes and hence defines them” (Millar, 2013, p. 55), there are mounting concerns, exacerbated by the Covid-19 pandemic, that learners will be provided with fewer opportunities to conduct practical work themselves (Cutler, 2020).

**Purposeful Practical work**

Practical work in this context refers to the collection of data through investigation, measurement, and observation of phenomena intending to develop students’ understanding of scientific methods and their ability to safely use apparatus and follow practical procedures (Abrahams & Millar, 2008). Purposeful practical activities are defined as those in which the teacher knows the purpose of the activity, which “should be planned and executed so it is effective and integrated with other science learning” (Gatsby, 2017, p. 45). Purposeful practical work requires that students consider “the thinking behind the doing” (Oshima & Roberts, 2018, p. 69) in addition to developing practical and investigative skills. The AQA examination specification states that by “focusing on the reasons for carrying out a particular practical, teachers will help their students understand the subject better, to develop the skills of a scientist and to master the manipulative skills required for further study or jobs in STEM subjects” (AQA, 2019a, p. 101). According to the specification, the reasons stated for doing practical work in schools are: to support and consolidate scientific concepts, to develop investigative skills, and to build and master practical skills.

Thus purposeful school practical tasks are those that facilitate the acquisition of complex cognitive skills; the integration and transference of attitudes, knowledge, and skills. Kirschner and van Merriënboer (2008) use the term “complex learning” to describe such acquisition of complex cognitive skills. However, research has indicated that school practical work is rarely purposeful (see Cukurova, Hanley, & Lewis, 2017 for a comprehensive review). Johnstone (2006, p. 58) suggests that the problems with practical work arise because of they become overwhelmed with “written and verbal instructions, unfamiliar equipment and chemicals, observing and recording”, leaving little capacity for cognitive processing. This context means that students try to manage the load by using “written instructions as a ‘mind-in-neutral’ recipe”.

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This work explores how practical activity designed to meet the AQA GCSE chemistry specification requirements may be adapted so that students are better able to answer practical-themed examination questions. To do so we will begin by considering factors known to impact upon students’ thinking and learning during complex tasks. Then we will consider a theoretical framework for exploring the impact of adaptations informed by these factors on students’ performance on practical-themed examination questions. As previously discussed there is an apparent dichotomy between the requirements of practical assessment on the one hand, and the demands of “purposeful practical work” on the other. For this reason, the analytical framework must consider not just its separate components the practical activity but the systemic whole recognising the existence of such contradictions. We will then demonstrate the framework and adaptations in action before discussing the implications this work has for practical activity.

**Theoretical Frameworks**

**Cognitivism**

Cognitive load is the term used to describe the demand placed on the working memory by a task, and cognitive load theory (CLT) applies what is known about human cognitive architecture to the study of learning and instruction. Briefly, when load becomes too high, learning is impaired (Chen, Castro-Alonso, Paas, & Sweller, 2018; Van Merriënboer, 1997; van Merriënboer & Kirschner, 2018). The importance of conducting hands-on practical tasks is supported by embodied cognition. Embodied cognition asserts that cognitive processes, including information processing and learning, are inextricably linked with all forms of sensory input (not just sight and sound) including physical and environmental experiences of an individual (Barsalou, 1999). Thus a learner’s motor functions, including gestures and tactile experiences, play a similar role to, and introduce similar effects as, visual and auditory information in learning. The importance of learners carrying out hands-on practical tasks is further supported by the distributed attention model of working memory (Sepp, Howard, Tindall-Ford, Agostinho, & Paas, 2019), specifically, that physical movement can expand working memory capacity (Bokosmaty, Mavilidi, & Paas, 2017).

Research in CLT has already identified several empirically supported effects that can inform teaching practice and the design of learning materials. For example, the ‘modality effect’ - using both auditory and visual channels – increases the capacity of working memory, and facilitates more effective learning (Jeung, Chandler, & Sweller, 1997; Mousavi, Low, & Sweller, 1995; Tindall-Ford, Chandler, & Sweller, 1997). The modality effect occurs in mixed-mode instruction when visual learning materials (such as diagrams) are supplemented with complementary auditory information, such as a verbal explanation in place of written text. Drawing upon instructional design for complex learning (van Merrienboer, Kirschner, & Kester, 2003), Seery, Agustian, and Zhang (2019) recommend that the two categories of knowledge that are required to understand and conduct a laboratory task are identified separately in curriculum design. The first is
“supportive information” – conceptual knowledge needed for the students to understand the task and the rationale of carrying it out, or what has been called the “the thinking behind the doing” (Oshima & Roberts, 2018, p. 69). The second is “procedural information” – procedural knowledge that enables students to successfully carry out the task. There is a clear shared purpose between the focus of Seery et al. on the undergraduate chemistry laboratory and Ofqual’s GCSE chemistry practical work discussed above. As such, these laboratory curriculum guidelines can be used to inform school practice. Indeed following the call from Agustian and Seery (2017) for renewed emphasis for inclusion of pre-laboratory activities within the overall framework of laboratory learning in undergraduate curricula, the benefits of pre-laboratory preparation in a secondary school context have already been reported (Hennah, 2019; Hennah & Seery, 2017).

Collaborative Learning

In schools, students habitually work in small groups of 2 to 4 learners when carrying out practical tasks, because of the need to share equipment (Christensen & McRobbie, 1994). However, group work can be viewed as advantageous. For example, Dillenbourg (1999) noted that social interaction between peers is fundamental to achieving learning. Moreover, Johnson and Johnson (1989) found classroom learning improves significantly when students participate socially, interacting in face-to-face collaborative learning activities with small groups of members. Jurkowski and Hänze (2015) report meta-analyses of educational studies that demonstrate positive effects of cooperative learning when compared to competitive or individual learning beyond knowledge acquisition which include social and motivational outcomes such as academic self-concept, social skills, and peer relationships.

Collaborative learning (Johnson & Johnson, 1989; Johnson, Johnson, & Smith, 1991, 1998) can be defined as a learning situation during which students actively contribute to the attainment of a mutual learning goal and try to share the effort to reach this goal (Teasley & Roschelle, 1993). Collaborative learning should result in every group member learning something from the combined effort. When working together, students not only interact, they ‘interthink’ (Littleton & Mercer, 2013). The use of language and other modes of representation enables learners to link their individual minds to create a more powerful information-processing system which Mercer (2013) describes as the “social brain”. Hands-on practical tasks afford students the opportunity to interact with each other as well as the procedures and materials of science. For example, a study of collaborative learning in a school laboratory reported an improvement in skill acquisition, conceptual understanding, and positive affective outcomes among the 12-year-old female participants (Raviv, Cohen, & Aflalo, 2019).

There is an argument, based on CLT, which suggests that collaborative group work during complex learning tasks could help to overcome individual working memory limitations (F. Kirschner, Paas, & Kirschner, 2009; F. Kirschner, Paas, Kirschner, & Janssen, 2011). Indeed, F. Kirschner, Paas, and Kirschner (2008) have shown
that learning by an individual becomes less effective and efficient than learning by a group of individuals as task complexity increases. Furthermore, according to CLT, learners in collaborative groups are considered as a single information-processing system as the processing is divided across the group (Tindale & Kameda, 2000), in what F. Kirschner et al. (2011) call “the distribution advantage”. Information must be recombined following division, and processing must be coordinated, but these costs are minimal compared to the gains from this division of labour when the cognitive load is high (F. Kirschner et al., 2009).

The question arises of how group work can be transformed into collaborative learning. (Leikin & Zaslavsky, 1999) advise that learning materials need to be modified so that every member of the group is responsible for contributing to the group work and the group’s success. Fransen, Kirschner, and Erkens (2011) – in the context of computer-supported collaborative learning – report that assigning roles within a collaborating team has positive effects on the team’s effectiveness. Frith and Singer (2008) noted that “when joint action requires cooperation, shared representations of task requirements and goals are very important to achieve better performance. Such sharing is referred to as common knowledge” (p. 3876). Edwards and Mercer (2013) describe the creation of “common knowledge” as an interactive, complex, and discursive process.

Drawing upon the literature cited above the importance of minimising learners’ cognitive load during hands-on practical tasks is made clear and that failing to do so impairs learning. Furthermore, understanding that practical tasks to be complex learning environments emphasizes instructional design and collaborative group work in which common knowledge is created, are means of lessening the cognitive load imposed by the task

### Sociocultural theory

In recognition of the potential benefits of student collaboration during practical work, we adopt a sociocultural approach (Vygotsky, 1978) which understands that knowledge is not transmitted from one individual to another but co-constructed through social interaction. Vygotsky (1978, p. 57) states: “Every function in the child’s cultural development appears twice: first, on the social level, and later, on the individual level; first, between people (interpsychological) and then inside the child (intrapsychological). This applies equally to voluntary attention, to logical memory, and to the formation of concepts. All the higher functions originate as actual relationships between individuals”.

To explore the process through which individuals’ learning is linked to their sociocultural context, Vygotsky conceived the Zone of Proximal Development (ZPD), which refers to the difference between what an individual can accomplish entirely on their own, and what they can do with the assistance of a more capable other (Cazden, 1981). The more capable other may be a teacher, tutor (human or electronic), or may arise through the structure of the activity (Smith, Hinckley, & Volk, 1991).

The application of sociocultural theory to chemistry education is well documented (see Finkenstaedt-Quinn et al., 2017; Flener-Lovitt, Bailey, & Han, 2020; Moon, Stanford, Cole, & Towns, 2017; Pazicni & Flynn, 2019...
as recent examples). Collaborative learning may be rationalised by Vygotsky’s (1978) concept of the ZPD because, a more capable learner can provide “scaffolding” (Wood, Bruner, & Ross, 1976, p. 90) for a less capable learner to accomplish a task that they could not accomplish alone. Adopting a sociocultural approach to learning understands education to be a dialogic process shaped by cultural and historical factors, and thinking, learning, and development cannot be understood without taking account of the intrinsically social and communicative nature of human life (Mercer, 2007).

Vygotsky’s notion of mediation suggests that the individual does not establish a direct relationship with the world, but that this relationship is mediated through the use of tools (Lantolf & Beckett, 2009). Sociocultural theory describes human mental functioning as a mediated process that is organised by activities, concepts, and cultural artefacts (Ratner, 2002). An example is chemical concepts; which are not tangible (Lemke, 1990), but constructed through meditational means such as language, symbols, and reproducing chemical phenomena. Indeed sociocultural theory provides further support for hands-on practical tasks as it is through social negotiation and participation in cultural activities that understanding is generated (Packer & Goicoechea, 2000).

Vygotsky viewed language as the primary mediational tool because it has both an intrapersonal and an interpersonal function that mediates learning and development (Lantolf, Thorne, & Poehner, 2015). Artefacts help individuals internalise social practices that are then externalised as cultural actions or behaviours. Watching a pre-laboratory video can be understood to be such an artefact, supporting support learners in carrying out a practical task. As such, adopting a sociocultural approach places emphasis on the quality of dialogue and collaborative social interactions arising out of these externalised practices.

**Cultural historical activity theory (CHAT)**

Cultural Historical Activity Theory (CHAT) is a theoretical framework that considers human cognition and development as products of social interaction in which artefacts of all kinds may be employed to learn and communicate (Engeström, 2008; Vygotsky, 1978). CHAT affords the opportunity to consider strategies to reduce the cognitive load of a task and improve learners’ collaboration and communication within the rigid confines of the National Curriculum.

CHAT has been widely utilised in education (for a comprehensive review see Nussbaumer, 2012; Plakitsi, 2013) and may be employed as a practical intervention methodology to improve learning because it provides a conceptual framework for understanding the inter-relationships between activities, actions, operations and artefacts, the subjects’ motives and goals, and aspects of the social, organisational, and societal contexts within which these activities are framed (Engeström, 2008).
CHAT is composed of seven components; subjects, objects, community, mediating artefacts/tools, rules, division of labour, and outcomes (Engeström, 1999). In CHAT, the relationship between subject and object is pictured as a triangle, known as the activity system (Figure 1). The activity system constitutes the minimal unit of analysis, a map of complex instructional activity within a single, integrated system (Roth, Lee, & Hsu, 2009).

Within the activity system, the subject may be an individual or group of individuals participating in a specified activity and the object is the motivating influence behind the subject’s participation in this activity. As shown in Figure 1 the subject acts upon the object, with actions is mediated by tools to produce the activity outcome. Wertsch suggests that artefacts or mediational tools cannot be separated from the process of achieving a goal and the mediation of knowledge and skills is dependent upon the tools used in the process of meaning-making (Wertsch, 1994; Wertsch & Rupert, 1993). The subject acts within a community in the context of rules that the entire community follows. Finally, division of labour describes how the tasks and responsibilities are shared among the participants engaged in the activity (Cole & Engeström, 1993).

It is important to appreciate that every aspect of the system affects and is affected by the other aspects constituting the activity that produces the outcome. The system is constantly working through contradictions within and between its elements meaning that, for example, rules, community, and the division of labour are all mediators and dialectically linked (Lee, 2011).

CHAT has been used in science education studies to consider processes as disparate as representations of science in textbooks (van Eijck & Roth, 2008), novice teachers’ transitions into teaching (Saka, Southerland, & Brooks, 2009), one student’s engagement in science classroom laboratory work (Andrée, 2012), pedagogic practices in informal science education contexts (DeWitt & Osborne, 2007), and culture and language-influenced curriculum materials in physics (Morales, 2017), and recently, university chemistry education (Keen & Sevian, 2022).

The GCSE chemistry practical activity system

The seven CHAT elements in the English GCSE chemistry practical activity system are illustrated in Figure 1. The subjects are the students who work in small groups to carry out the practical task, and the object is purposeful practical work. The object can be thought of as an objective, leading to the outcome being the quality of student responses to practical-themed exam questions, as measured using the exam board mark scheme (AQA, 2021).

The tools or mediating artefacts include technical tools such as laboratory equipment that help the subject effect things; psychological tools such as written instructions in lab books, and verbal instructions and visual images in practical videos or teacher demonstrations; and other people such as the teacher and fellow learners via scaffolding or ZPD. Although any one or more of the mediators in the activity system can be
foregrounded, the rest remain indispensable to describe the methods and motives behind the subjects’ transformations of the objects. This latter process is equivalent to learning, the mutual transformation of object and subject during practical activity (Leont’ev, 1978).

The rules refer to the explicit and implicit conventions and regulations that regulate the actions and interactions within the activity system (Engeström, Engeström, & Suntio, 2002) specifically laboratory conventions and teacher expectations. The community refers to individuals/groups who broadly share the same object and consider themselves distinct from other communities, which is a particular class of learners and their teacher within a particular school. The community is subject to the ideological values advocated by the Department for Education, and privileged in England’s education system which is, arguably, a reflection of the Organisation for Economic Co-operation and Development (OECD, 2019) current globalised ideologies. Finally, the division of labour includes both the division of tasks between the members of the community and the vertical apex which embodies the division of power and status (Gifford & Finkelstein, 2020).

The interplay between the elements of an activity system can provide new opportunities for learning and for change (Engeström, 2001) and it is through interaction in a shared activity that the subject adjusts their thinking and behaviour to bring about a change (Bligh & Fathima, 2017).

![Figure 1: The seven CHAT elements in an English GCSE chemistry practical activity system](image-url)
Objectives and Research Questions

Recognising hands-on practical tasks as complex learning environment, this work draws upon cognitivism to inform novel instructional approaches designed to lower the cognitive load imposed on individual learners’ working memories by the task. The novel instructional approaches includes pre-laboratory preparation videos “one video two voice over”, in which procedural and concept information has been separated, and talk tasks “reverse storyboarding” designed to encourage learners to recall the procedure before carrying out the task. Cognitivism and sociocultural theory are employed to develop a cooperative learning environment by assigning roles, “Lab Roles” to structure student-student interactions during the implementation of the task. As sociocultural theory emphasises the importance of talk as a mediating tool for the construction of knowledge, roles “Lab Talk” that scaffold student-student talk have also been introduced. Finally, the activity that results from these modifications is holistically addressed through the application of cultural historical activity theory (CHAT). CHAT is applied to this work to understand the interplay of factors that impact learners carrying out a practical task activity. Within the CHAT framework, we examine the impact that different instructional approaches have on the activity outcomes.

This work seeks to establish the use of cultural-historical activity theory (CHAT) as a framework for developing and implementing laboratory activities in chemistry education. The authors believe that the framework comprehensively identifies the interacting factors that impact the implementation and outcomes of hands-on practical tasks and is relevant to both high schools and postsecondary education. The study contributes to the existing knowledge of laboratory instruction by demonstrating the use of assigned roles to facilitate establishing a more equitable, cooperative, and inclusive learning environment.

Research questions

1. Are there significant differences in summative test attainment scores between students exposed to Lab Talk and Lab Roles and their counterparts not exposed to this approach?
2. What influence does the inclusion of one video two voice-overs have on students’ perception of their learning experiences?

Context of the study.

The students in this study attend an English academy for boys aged 11 to 18 in an area the Social Mobility Commission (2017) ranked 35th of the worst of the 324 areas of the country for social mobility for those from disadvantaged backgrounds. Students are given forecast grades for GCSEs based upon their Key Stage 2 (KS2) results from primary school (age 10 to 11 years). Targets are generated from each student’s KS2 English reading and mathematics test attainment scores, their month of birth, and gender. National
transition matrices derived from high-performing schools use this data to generate a minimum achievement grade (MAG) for each student for the end of Key Stage 4 (KS4) when the GCSE exam is taken. This MAG is the baseline from which stakeholders can judge if a student or a class has been successful.

Three GCSE chemistry groups within the same school, following the same course, and in the same year group were used for this study. However, each group was taught by a different experienced specialist chemistry teacher. Groupings are determined by course options and timetable considerations, each class has a 30 student capacity. The groups are composed of 30 males aged between 14 and 15 years old with MAGs ranging from 4 to 7, where the maximum grade achievable is 9. The groups have been named Control, Video, and Talk for this study. The average MAG for each group was calculated group; Control = 6.5, Video = 6.4, Talk = 6.1, which suggest that the groups have a similar average ability. The AQA exam board reported that in 2019 62.2% of students following the same course nationally gained a grade 6 or below (AQA, 2019b).

The work was conducted in compliance with the British Education Research Association ethical guidelines (BERA, 2018), aligning with the principles of informed consent, right to withdraw, and guarantee of anonymity. In this system, the school Headmaster acts as an overseer of all actions conducted in the school, and permission to complete this research was confirmed by him. This was followed by permission from relevant staff and students (student participants were over 13 years old). In seeking permission, students were informed about the research and their right not to participate, and to withdraw at any time. All data collected and used during this research was securely stored.

The activity triangle tools

At the beginning of a practical task, students are introduced to the equipment and procedures involved. Health and safety issues are discussed before they are allowed to proceed. This pre-laboratory introduction is usually made through either teacher demonstration, video, or a combination of the two. The nature of this pre-laboratory has developed in response to concerns about the efficacy of school practical work as a tool for learning (see Hennah, 2019 for a brief review). Enabling learners to become familiar with equipment and procedures before undertaking the activity aims to lower the cognitive load imposed by the task and so alleviate the students’ ‘mind-in-neutral’ (Johnstone, 2006, p. 58) reliance on written instructions. Written instructions are also provided by a lab book that is only available to the students during the lesson as it is kept in school as evidence of practical work for the exam board.

Teacher demonstration

The teacher of the Talk Group habitually begins a practical task by discussing and demonstrating how to set up the equipment and carry out the task before the students carry out the task themselves. The
Temperature Changes practical task was conducted in this habitual manner to afford the Talk Group with an experience that contrasted to the intervention tasks.

Video

As technology has developed there is an increasing interest in the use of multimedia as an instructional tool to teach science in schools (Higgins, Moeed, & Eden, 2018). Videos, simulations, and written accounts of practical activities in textbooks and other written resources are used to supplement hands-on practical work or teacher demonstrations (Moore et al., 2020).

Within this research setting, it has become increasingly common practice to replace a teacher demonstration with a video of the task and discussion immediately before the students carrying out the task themselves both the Control and Video Groups. The videos used by the Control Group instead of a teacher demonstration of the materials and methods were:

- **Making Salts** https://www.youtube.com/watch?v=FRaT0qOKZpU (4:40) and

For this study tailor-made videos showing each step of the procedure were produced for the Making Salts and Electrolysis practical tasks. Drawing upon CLT as previously described, particularly the Seery et al. (2019) recommendation that the two categories of knowledge required to understand and conduct a laboratory task are identified separately, a separate procedure voice over and concepts voice over were produced. In response to Johnstone’s (2006) concerns outlined above, this approach affords learners with the opportunity to become accustomed to the practical activity and to consider separately what to do and why it is done.

The videos can be accessed as follows:

- **Making Salts** procedure https://www.youtube.com/watch?v=gShUaHxghsl (6:57)
- **Making Salts** concepts https://www.youtube.com/watch?v=7X6dCPr2gi (6:26)
- **Electrolysis** procedure https://www.youtube.com/watch?v=xy3KmE-y5WQ (6:43)
- **Electrolysis** concepts https://www.youtube.com/watch?v=4GGcApT54gE (7:45)

Informed by instructional design for complex learning (van Merrienboer et al., 2003) separating the information in this way could help to lower the cognitive load of the task. The procedural voice over video was watched before the hands-on task was carried out to prepare the students and the same video but with a procedural voice over was watched following completion of the task to aid reflection and understanding of the concepts that underlie the procedure.

To investigate the efficacy these “one video two voice over” videos compared to the Control Group videos as an instructional approach they were watched by the Video Group. The Video Group watched the “one video two voice over” materials in the lesson immediately before and after the hands-on task.
The Talk Group were set the procedure video as a pre-laboratory home learning task (Agustian & Seery, 2017) to be watched prior to the practical lesson and the concept video was set as a home learning task to be completed before the following lesson. In this manner using the videos does not impact on the lesson time available for the practical task.

**Lab Books**

Each student within the research setting is issued with a commercially available lab book (Quinn, 2018). However, the lab book is only made available to the students during the activity lessons. The lab book contains a written method and safety information alongside blank sections for recording data and answering follow-up questions. During practical work, the lab book may be used by the teacher to highlight health and safety issues and to discuss the written method. The same chemicals and laboratory equipment as detailed in the lab book are available to all three groups.

Hands-on practical tasks are completed within a 90-minute double lesson and a 45-minute single lesson in the same week is used to discuss the practical and for students to complete the lab book questions. A practical task is considered complete when the lab book activities have been finished and the teacher has provided feedback.

**Reverse Storyboarding**

Storyboarding is a standard method for visual summarisation of shots in preproduction video whereas, reverse storyboarding is the term used to describe visual summarisation of existing video footage (Dony, Mateer, & Robinson, 2004). The Talk Group were asked to watch the “one video two voice over” procedure video as a home learning task to be completed before the practical lesson. The Talk Group were then asked to complete the reverse storyboard which summarised the procedure video and asked why that action was necessary. Using a storyboard in this way facilitates active learning which Barnes (2010) describes occurs through talk, whereby ideas are shared and shaped between interlocutors, forging links between new and existing knowledge to create common knowledge. Furthermore, the storyboard allows the students to share their understanding which can positively impact upon collaboration (Frith and Singer, 2008, p. 3876). The completed storyboard was checked by the teacher and then the students were issued with their lab books and allowed to complete the practical.

**The activity triangle division of labour**

Both the Control and Video Groups have teacher designed seating plans but are allowed to choose who they conduct practical work with. The Talk Group students were seated alphabetically and further organised into groups of three based on their seating position. Their teacher established and then maintained these groups beyond the confines of our data collection to all practical activities so they became accustomed to this style of working. Prior experience collaborating as a team can increase efficiency and performance and the
number of transactional activities decreases, lessening the cognitive load experienced by established groups compared to ad hoc ones (P. Kirschner, Sweller, Kirschner, & Zambrano, 2018). Changes from the generalised activity system (Figure 1) incorporating these changes for the Talk and Video groups are shown in Figure 2 for clarity.
Lab Roles

Drawing upon Leikin and Zaslavsky (1999) and Fransen et al. (2011) as previously discussed, the Talk Group had been organised into groups of three and given lab roles for all their practical tasks so they were accustomed to this style of working. Grouping students as trios rather than pairs reduce issues caused by a group member being absent whilst still being a small enough grouping for everyone to be engaged. The roles delineate the contributions each member is expected to make (Gaunt & Stott, 2018) and were devised from those previously reported (Ott, Kephart, Stolle-McAllister, & LaCourse, 2018). As shown in Figure 3, the three lab roles were rotated within each group so that every student had experienced each role.

![Lab Roles](image)

**Lab Roles**

- You have been assigned to lab groups of 3.
- Decide who is A, B and C.
- Record which role you have taken during this practical.
- You must complete all of the tasks assigned to this role.
- Next practical lesson you will swap roles A to B, B to C, C to A.

A. Technician
- ✓ collect and set up equipment
- ✓ record results
- ✓ rinse used equipment
- ✓ return equipment after use

B. Materials handler
- ✓ collect all chemicals
- ✓ make measurements
- ✓ handle chemicals
- ✓ return chemicals after use

C. Manager
- ✓ coordinate group to perform the task
- ✓ organise the activities
- ✓ direct procedure
- ✓ manage safety,
- ✓ manage tasks and time
- ✓ objective setting and performance appraisals

Figure 3: Talk Group lab roles and corresponding responsibilities during hands-on practical work.

Lab Talk

A great deal of work has been done to develop argumentation in chemistry education (see Erduran, 2019 for a comprehensive review) and the benefits of scaffolding younger learners’ talk in science have been reported (Mercer, Dawes, Wegerif, & Sams, 2004; Rojas-Drummond & Mercer, 2003). However, assigning specific talk roles and protocols to scaffold laboratory discussion has yet to be reported. Gaunt and Stott (2018) detail a range of talk roles and protocols from which Lab Talk has been developed. The same student
Trios are used for Lab Roles and Lab Talk. Figure 4 illustrates the Talk Roles and protocol used during the reverse storyboarding activity. The students were encouraged to try to continue following this talk whilst conducting the practical activity.

Enforcing a structured division of labour by using lab roles and lab talk necessitates recognising that new rules are also being introduced as these practices are mandatory.

**Lab Talk: Use these talk roles to discuss and reach a consensus of opinion.**

<table>
<thead>
<tr>
<th>Procedure Storyboard Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>What? use the image on the story board to recall and discuss the procedure and safety steps demonstrated in the video.</td>
</tr>
<tr>
<td>Why? Drawing on your chemistry knowledge suggest why are the procedure and safety steps are necessary in this method.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A Asks questions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why...?</td>
</tr>
<tr>
<td>What do you think of ...?</td>
</tr>
<tr>
<td>What are the implications for ...?</td>
</tr>
<tr>
<td>How might ...?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B Begins/Builds:</th>
</tr>
</thead>
<tbody>
<tr>
<td>I think this shows ...</td>
</tr>
<tr>
<td>This suggests that ...</td>
</tr>
<tr>
<td>One thing that stands out is ...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C Contests/continues:</th>
</tr>
</thead>
<tbody>
<tr>
<td>In addition it could imply ...</td>
</tr>
<tr>
<td>Also I think this tells us ...</td>
</tr>
<tr>
<td>I disagree with you because ...</td>
</tr>
</tbody>
</table>

**Figure 4:** scaffolding the Talk Group’s storyboard discussion using Talk Roles that correspond to their Lab Roles.

**Methodology**

Drawing upon cognitivism and sociocultural theory, this work adopts a quasi-experimental design to investigate learning outcomes from GCSE chemistry practical tasks using a CHAT activity system. Engeström (2001) claimed that the interplay between the elements of an activity system can provide new opportunities for learning and for change. Here, changes to the English GCSE chemistry practical activity system’s tools, division of labour, and rules are made and the resultant outcomes measured. Because learning, identity, and emotions are interdependent (Damasio, 1994; Wenger, 1998) affective data and student interview data have been collected.
Three GCSE curriculum practical tasks *Temperature Changes, Making Salts, and Electrolysis* (AQA, 2018) were selected for this study based upon their occurrence within the school calendar. Table 1 summaries the groups and the activities involved in this study.

<table>
<thead>
<tr>
<th>Group</th>
<th>GCSE chemistry practical task</th>
<th>Pre-laboratory home learning task</th>
<th>Hands-on lesson explication</th>
<th>Plenary task</th>
<th>Post-laboratory home learning task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>Making Salts</td>
<td>Video</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>Electrolysis</td>
<td>Video</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Video</td>
<td>Making Salts</td>
<td>Video (procedure)</td>
<td>Video (concepts)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Video</td>
<td>Electrolysis</td>
<td>Video (procedure)</td>
<td>Video (concepts)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talk</td>
<td>Video (procedure)</td>
<td>Reverse storyboard</td>
<td></td>
<td>Video (concepts)</td>
<td></td>
</tr>
<tr>
<td>Talk</td>
<td>Video (procedure)</td>
<td>Reverse storyboard</td>
<td></td>
<td></td>
<td>Video (concepts)</td>
</tr>
<tr>
<td>Talk</td>
<td>Temperature changes</td>
<td>Teacher demonstration</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: A summary of the student groups, which hands-on practical tasks they have undertaken, and how they have been prepared for it.

**Data Collection**

**Quiz**

The students from all three groups were given a paper quiz composed of practical-themed examination questions in the lesson immediately before beginning their practical task. The same quiz was administered to all three groups at the beginning of the chemistry lesson that immediately followed the practical task. This was done as a measure of student knowledge directly prior to, and following from the practical task. Although the quiz papers were anomalous students were asked to provide their MAG to facilitate data analysis. Quizzes belonging to students who were not taking part in the research were immediately disposed of.
Table 2: a summary of each group’s video preparation and quiz data collection for the *Making Salts* and *Electrolysis* practical tasks.

All the student responses were collected together and marked blind using a matrix corresponding to the exam board mark scheme and examiner reports for the practical-themed examination questions used in the quizzes. Cohen’s kappa was used to determine the agreement between the judgments $k = 0.770$ (95% CI, .564 to .975), $p < 0.0005$. Normality checks and Levene’s test of homogeneity have been conducted on the participants involved in each test as a combination of absenteeism and students choosing not to return quiz responses has led to variations in the quantity of data gathered during each iteration (see Table 2).

**Qualitative data**

The three groups had completed the *Making Salts* and the *Electrolysis* practical tasks and a third practical task, *Temperature Changes*, before they were asked to complete the paper questionnaires. The purpose of the inclusion of a third practical task without “one video two voice over” videos, reverse storyboards nor roles was to provide the Video and Talk Groups with a comparable experience before responding to the questionnaire. The paper questionnaires belonging to students who were not taking part in the research were immediately disposed of.

**Results**
Research Question 1. Are there significant differences in summative test attainment scores between students exposed to Lab Talk and Lab Roles and their counterparts not exposed to this approach?

Making Salts Quiz Results

A one-way ANOVA was conducted to compare the Minimum Attainment Targets (MAG) of the three groups, Control 1 \((n = 22)\), Control 2 \((n = 22)\), Video 1 \((n = 22)\), Video 2 \((n = 25)\), Talk 1 \((n = 24)\), Talk 2 \((n = 29)\). Group names followed by a ‘1’ indicate quiz results obtained before completing the practical task, while those followed by a ‘2’ refer to the second iteration of the quiz which was taken in the chemistry lesson that immediately followed the practical activity. There was no statistically significant variance in the mean MAG between the groups \([F = 1.142, p = 0.341]\). Levene’s test supports the null hypothesis that group variances are equal.

Making Salt Quiz attainment z-scores for each of the groups have been plotted as box plots (Figure 5). A one-way ANOVA was conducted to compare the effectiveness of the three pedagogic approaches \(F(5,135) = 43.035, p = 0.0005\). Post hoc tests using the Bonferroni correction revealed that only the Talk Group showed a statistically significant difference between their test z-score 1 and z-score 2 \((p = 0.0005)\). The Talk Group performed significantly better on both tests than both the Control and Video Group \((p = 0.0005)\).
Figure 5: Z-scores for student responses to the *Making Salts* practical-themed examination-style quiz questions. Where 1 following the group name refers to the quiz taken before the practical task and 2 refers to the quiz taken after the practical task.

**Electrolysis Quiz Results**

A one-way ANOVA was conducted to compare the Minimum Attainment Targets (MAG) of the three groups Control 1 \((n = 7)\), Control 2 \((n = 18)\), Video 1 \((n = 15)\) Video 2 \((n = 25)\) Talk 1 \((n = 19)\) Talk 2 \((n = 21)\), with group name convention as described above.

Normality checks and Levene’s test of homogeneity were carried out and the assumptions were met. There was no statistically significant variance in the mean MAG between the groups \([F = 0.431, \ p = 0.826]\) Levene’s test supports the null hypothesis that group variances are equal.

**Electrolysis** Attainment z-scores for each of the groups have been plotted as box plots (Figure 6). A one-way ANOVA was conducted to compare the effectiveness of the three pedagogic approaches \(F(5, 98) = 25.43, \ p = 0.0005\). Post hoc tests using the Bonferroni correction revealed that both the Video \((p = 0.008)\) and Talk \((p = 0.0005)\) showed statistically significant difference between their test z-score 1 and z-score 2 \((p = 0.0005)\). The Talk Group performed significantly better on both tests than both the Control and Video Group \((p = 0.0005)\).
Figure 6: Z-scores for student responses to the Electrolysis practical-themed examination-style quiz questions. Where 1 following the group name refers to the quiz taken before the practical task and 2 refers to the quiz taken after the practical task.

Research Question 2. What influence does the inclusion of one video two voice-overs have on students’ perception of their learning experiences?

Questionnaire
Each of the Control, Video and Talk groups were issued with a questionnaire to complete following a third practical task – Temperature Changes – which was conducted without the use of “one video two voice over” videos, storyboards or laboratory roles, approximately four weeks after the completion of the Electrolysis task. The questionnaires were tailored to compare the students perceived practical task experience. All items are responded to on a Likert scale of 1 – 5, where 1 = Strongly Disagree and 5 = Strongly Agree. Each group had a questionnaire tailored to their experience and as such the reliability of each questionnaire was calculated separately. Reliability analysis was carried out on the Control Group’s questionnaire responses comprising 12 items. Cronbach’s alpha showed the questionnaire to reach acceptable reliability, α = 0.972, Video Group’s questionnaire comprising 26 items, α = 0.991, and a reliability analysis was carried out on the Talk Group’s questionnaire responses comprising 42 items, α = 0.995.

Figure 7: Students’ questionnaire responses to questions concerning Making Salts practical task (1 = Strongly Disagree; 5 = Strongly Agree).
The students’ responses to the questionnaires have been grouped in the bar charts shown (Figures 7 and 8), noting that a higher average indicates greater agreement. All three groups agreed that carrying out the Making Salts and Electrolysis practical tasks increased their understanding of the underlying scientific ideas. Both the Talk and Control Groups agreed that they feel confident about answering Making Salts and Electrolysis theory questions although the Talk Group showed the strongest agreement in each case. The Talk Group’s scores in Figures 5 and 6 support their confidence.

The greater confidence expressed by the Talk Group than the Video Group seen in Figures 7 and 8 indicates that watching the video as a home learning task rather than immediately before carrying out the practical is beneficial. However, the Video Group’s scores may in part have resulted from the video’s poor sound quality reported by their teacher when watching the videos in the lesson.

Figure 8: Students’ questionnaire responses to questions concerning Electrolysis practical task (1= Strongly Disagree; 5 = Strongly Agree)
Figure 9: Students’ questionnaire responses to questions concerning the use of video in preparing for practical tasks and practical-themed exam questions (1 = Strongly disagree; 5 = Strongly Agree)

The average Likert scores presented in Figure 9 demonstrate that having watched the “one video two voice over” videos for both the Electrolysis and Making Salts practical task has had a positive effect on the Talk Group students’ confidence in learning. The Likert scores indicate that watching both versions of the video had the most positive effect on the students’ confidence.

Discussion

In chemistry education research, university laboratory learning has been recognised as a “complex learning environment” (Seery, et al., 2019), which aims to guide use of instructional approaches designed to support student learning in this environment (van Merrienboer et al., 2003). Purposeful practical work in the school laboratory, as previously discussed, is that which also facilitates the acquisition of complex cognitive skills. For this reason, adopting the strategies identified by Seery et al. should also be of benefit to schools. However, schools in England, are not free to set their chemistry examinations and associated curricula. Indeed, the assessment criteria of GCSE practical work and purposeful practical work appear to be a contradiction in terms. Existing research from cognitivism (F. Kirschner et al., 2009; F. Kirschner et al., 2011) and sociocultural theory (Rojas-Drummond & Mercer, 2003) both reported that student learning was improved when group activities, including laboratory tasks (Raviv et al., 2019) were conducted collaboratively. CHAT enables all of these elements to be considered simultaneously as an activity system. Here, purposeful practical work was the activity’s object and was be understood in terms of practical-themed exam style question outcomes. CHAT places thought and learning as products of social interaction.
in which tools are employed to facilitate learning and communication (Engeström, 2008). In doing so hands-on practical work becomes a dialogic process central to learning. Changes were made to the activity system adding the “one video two voice over” videos as tools designed to reduce the cognitive load imposed on an individual’s working memory, and adding to the rules and division of labour within the group the mandatory Lab roles and Talk roles. The research questions described above were devised to investigate the impact of these changes on the activity system.

**Research Question 1**

The first research question intended to explore whether there were significant differences in test attainment for students who engaged in Lab Talk and Lab roles, and between these groups and those students were not exposed to this approach. The number of students returning completed quizzes varied between quiz 1 and quiz 2 and between quiz groups suggesting some students may have only submitted one response. For this reason, a one-way ANOVA was conducted to compare the Minimum Attainment Targets (MAG) of the three groups for each iteration of the quiz to confirm that there was no statistically significant variance in the mean MAG between the groups.

Referring to the standard score box plots of group performance in *Making Salts* quiz 1 and 2 (Figure 5) and *Electrolysis* quiz 1 and 2 (Figure 6), the Talk Group performed better in the quizzes than either the Control or Video Groups and the lowest attainment scores were obtained by the Control Group. However, only the Talk Group performed statistically significantly better in quiz 2 than quiz 1 for both the *Making Salts* and *Electrolysis* tasks. Comparing the quiz 1 results for the three groups indicates that the “one video two voice over” procedure video watched by the Talk and Video Groups better prepared the students for the practical-themed exam questions than the Control Group’s videos. Then comparing the Video and Talk Group average score for quiz 1 suggests that watching the procedure video in advance of the lesson followed by the reverse storyboarding activity using Talk roles better prepared the students for the practical-themed exam questions than just watching the procedure video. Comparing the three groups’ quiz 2 results indicates that completing the practical task has improved their attainment in practical-themed exam questions. However, the quiz 1 and 2 attainment scores for the Control and Video Groups *Making Salts* task and the Control Group’s *Electrolysis* task were not statistically significant. This may advocate that further intervention, beyond watching a concepts video, is necessary to produce a significant improvement in the practical-themed exam questions attainment. However, as the Talk Group’s quiz 2 attainment scores improved with statistical significance compared to their quiz 1 scores for both practical tasks it is plausible that this may be attributed to the use of Lab roles during the practical task in combination with watching the “one video two voice over” concepts video after the lesson. Johnstone (2006) describes the role of pre-lab preparation plays in reducing the cognitive load imposed by the practical task, within the CHAT framework, this role is further extended to facilitate active learning (Barnes, 2010), and the construction of “common knowledge” (Frith
and Singer, 2008, p. 3876) among group members. Furthermore, the reverse storyboarding activity provided an opportunity for the Talk group student trios to form the shared representation of the task needed for effective collaboration (Frith and Singer 2008). The use of Lab Roles to impose a change in the activities system’s division of labour may also improve collaboration during the activity but it also changes the distribution of power and status as a particular student fulfilling a particular role becomes the most knowledgeable concerning that role and may have to share that knowledge so the group successfully complete the task.

The “one video two voice over” materials given as home learning activities and used in conjunction with Lab roles, reverse storyboards, and Talk roles produce the highest average attainment scores which suggest that scaffolding collaborative tasks and student talk further enhance the benefits provided by reducing the task cognitive load by separating the two types of knowledge needed for the activity. Further work would investigate each treatment separately to identify the greatest effect and to then apply this understanding to augment the impact of the concepts video.

The existence of a contradiction between the requirements of practical assessment and purposeful practical work is made visible by using the CHAT framework despite which, instructional adaptions informed by sociocultural theory and cognitivism have been shown to make statistically significant improvements to students’ performance on practical-themed examination questions. The contradiction stems from the activity system’s community element where the ideological values advocated by the Department for Education as represented by AQA and those advocated by scientists as represented by Gatsby foundation differ. Although teachers nor schools may change the assessment requirements of GCSE examinations, there is scope for the use formative assessment of school practical work prior to GCSE study. Furthermore, this work suggests that when learners understand the purpose of a practical task, they are better able to achieve the intended outcome whereas, purposeful practical activities have been defined in terms of the teacher knowing the purpose of the activity (Gatsby, 2017, p. 45) a point that could be addressed by the system’s rules.

**Research Question 2**

The second research question intended to explore the extent of influence of the “one video two voice overs” on students’ perception of their learning experience and reported learning gains. The Video and Talk Group students’ perception of their learning experiences and learning gains from the use of the “one video two voice over” materials are given in Figures 7 and 8 which refer to the *Making Salts* and *Electrolysis* tasks respectively. Generally, the Talk Group reports greater confidence having watched the “one video two voice over” videos than the Video Group. This may be in part attributed to differences in the way the videos were watched. The Video Group watched the videos in the lesson whereas the Talk Group watched them outside.
of the lesson as a home learning task. It is not possible to distinguish between the effect of the less public environment or having more time to reflect on the procedure videos that have caused this increased confidence. It is interesting to observe that the Talk Group is less confident about the impact of the concepts videos than the procedure videos which may result from the absence of an active learning activity similar to the reverse storyboarding activity to accompany this video.

Students from all three groups indicate that practical task increases their confidence in answering practical-themed exam style questions. These results contrast with concerns raised earlier about the efficacy of practical tasks as learning tools. Indeed this work has presented several arguments in favour of the inclusion of hands-on tasks which include sociocultural consideration, embodied cognition and distributed attention model of working memory (Sepp et al., 2019). It can also be observed that in every instance the Video Group reported a lower confidence value than the both the Control and Video Groups. For this reason it is logical to infer that additional factors not identified by this study are also having an impact on student confidence which provides scope for further study.

Referring to Figure 9, the Talk Group report a greater confidence in the impact that the procedure video has on their learning than the concepts video. Investigating the students’ perceptions of the impact of the concept video in conjunction with the development and implementation of the post-laboratory task offers scope for future work. The students also report that they are likely to watch the videos again when revising offers scope to investigate the design of revision videos for practical assessment through written examinations.

Conclusions

Cultural Historical Activity Theory has provided a useful framework for identifying interventions that could assist learners in carrying out purposeful practical work. Recognising the factors over which the classroom teacher has little or no control – that is the community – negates discussions about the purpose of the practical task accepting instead that task is directly linked to preparing the learner for their GCSE chemistry examination. Accepting the importance of the division of labour could disrupt existing divisions of power and status, and create more equitable activity as familiar teams take turns to adopt different Lab Roles and different Talk Roles. This, in turn, may positively impact student’s identity and science capital. Making changes to the division of labour requires considering existing laboratory rules and how they need to be modified to incorporate such changes. The Talk Group report the most positive responses to the questionnaire which suggests that the interventions have resulted in a generally positive experience and their attainment data suggests that this positive experience has, in turn, produced positive results. Placing greater emphasis on how students talk during the activity as well as what they talk about by using
storyboards recognises that education is a dialogic process and that language places emphasis upon is a “cultural and psychological tool” to accomplish an activity (Mercer, 2007, p. 137).

Limitations

A Quasi-Experimental Design was used to assess the effectiveness of the intervention without random assignment. Control and treatment groups were judged using their MAG rather than using pretest and z-scores were used to compare like with like. However, the groups selected cannot always be guaranteed to be alike in all possible ways expected. The outcomes of the study may be affected by many other factors, for example an unanticipated event reduced the number of students available to participate in the Control Group’s Electrolysis quiz 1. There will also be differences in how the activities are implemented such as the verbal instructions or how techniques are performed because each group is taught by a different teacher. To ameliorate these limitations, two practical tasks Making Salts and Electrolysis were used to increase the validity of the study so attainment could be compared between tasks as well as between groups.

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References


