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Hancock, Laura m.

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Laura M. Hancock*

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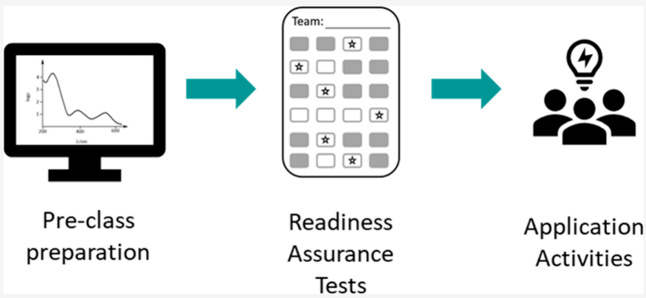

ABSTRACT: Team-based learning (TBL) has been gaining increasing attention in chemistry teaching, although it remains relatively under-exploited, especially compared to management and medical sciences. This study explores student perceptions of team-based learning as an active learning technique in an advanced inorganic chemistry topic. It focuses on qualitative research methods using thematic analysis of data collected through questionnaires and a focus group. Students were found to strongly associate TBL with being an effective active learning experience, where interaction with the pre-class preparatory materials is incentivized by the accountability they feel to their team members. The highly structured nature of TBL, where learning, assessment, and clarification of the core concepts takes place before more challenging problem solving, was highlighted, alongside the importance of the instructor in the TBL process. The importance of interactivity in the pre-class materials and alignment of the TBL materials with the end of course assessment was also emphasized. Students are hugely positive about TBL as being effective for the learning of challenging problem-solving topics, but are reticent to acknowledge that the flipped classroom model can be more effective than lectures.

KEYWORDS: *Team-based Learning, Active Learning, Collaborative Learning, Advanced Inorganic Chemistry*

■ INTRODUCTION

Active learning strategies have been shown to lead to improved student learning in STEM subjects.[1] Prince defines active learning as "*any instructional method that engages students in the learning process*".[2] Michael [2006] has outlined five key principles of active learning (Table 1).[3]

Table 1. Key Principles of Active Learning[3]

key principles	description
constructivism	*"Learning involves the active construction of meaning by the learner."*
problem solving	*"Learning facts and learning to do something are two different processes."*
knowledge transfer	*"Some things that are learned are specific to the domain or context in which they are learned, whereas other things are more readily transferred to other domains."*
collaboration	*"Individuals are more likely to learn more when they learn with others than when they learn alone."*
explanation articulation	*"Meaningful learning is facilitated by articulating explanations, whether to one's self, peers or teachers."*

There is an extensive range of active learning techniques which have been used in the chemistry classroom, spanning from simple exercises, which can easily be incorporated into existing classes, to specific highly structured instructional techniques. Arthurs and Zo Kreager suggest these activities can be categorized into four groups: (1) individual nonpolling activities (e.g., construction of a concept map[4]); (2) in-class polling activities (e.g., use of electronic voting devices[5]); (3) whole class discussions (relating to an activity[6]); and (4) in class collaborative group activities.[7] The final category incorporates the aforementioned structured instructional techniques. Common examples in chemistry education include Problem-Based Learning, Process-Oriented Guided Inquiry Learning, Peer-Led Team Learning, and more recently, Team-Based Learning.

To create time for activities that promote active learning, many chemistry educators have chosen to flip the classroom.[8] A fundamental principle of the flipped classroom is pre-class preparation, most commonly in the form of video lectures[9−13] or screencasts.[14−20] The advantages of the pre-class preparation are that students feel prepared for class,[9] it is possible to review the materials independent of time and location[16,21] and it provides a structure to out of class work.[19] There are a range of in-class activities incorporated in examples of the flipped chemistry classroom, however they generally involve group work in some form, often in combination with instructor intervention. There

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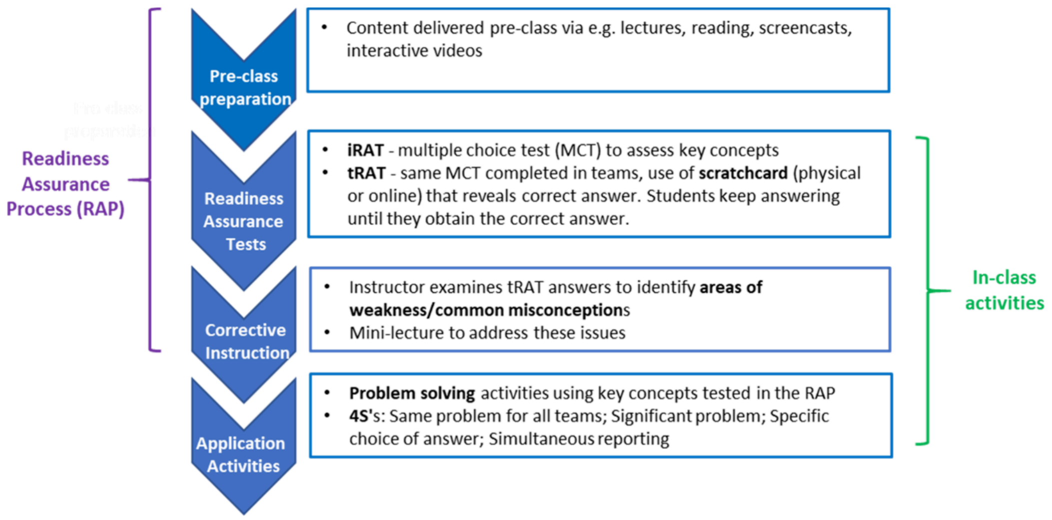

Figure 1. Sequence of activities in Team Based Learning. iRAT = Individual Readiness Assurance Test. tRAT = Team Readiness Assurance Test.

are several examples of instructors dedicating the first part of the class to addressing issues and misconceptions that students may have had with the pre-class material,[10,17,20] thus providing a link between the pre-class and class activities which may assist the scaffolding of knowledge. Shattuck[9] and Bokosmaty[11] implemented intervention mini-lectures interspersed between group problem solving.

In general, student feedback for classroom flipping in chemistry is overwhelming positive, with perceptions that collaborative learning enhanced understanding[9] and allowed opportunity to become autonomous learners.[10] "Social loafing" has been cited as the main disadvantage to group work[10] while difficulties with time management to complete the pre-class activities[15] and the lack of lectures[16] are also noted.

Team-Based Learning

Team-Based Learning (TBL) is a highly structured collaborative instructional technique that comprises a specific sequence of activities, summarized in Figure 1.

The TBL process has two main stages; the Readiness Assurance Process and Application Activities. The *Readiness Assurance Process* comprises *Pre-class Preparation* followed by the *Readiness Assurance Tests and Corrective Instruction*. These are designed such that students have a basic understanding of the core concepts in a topic to apply to more complex problems in the *Application Activities*. TBL is most often deployed in a flipped classroom model, where lectures are replaced with a series of tasks completed outside the classroom termed the Pre-class preparation (commonly reading or short video lectures/screencasts). The TBL workshop itself begins with the individual *Readiness Assurance Test* (iRAT), a multiple choice test designed to assess students' understanding of the background material. This test takes place individually without discussion or consultation with course materials. At this point, the answers are not revealed to the students. Following the iRAT, the exact same questions are used for the team *Readiness Assurance Test* (tRAT), where students discuss and debate their MCQ answers. The tRAT uses instant feedback scratch cards,[24] either hardcopy or electronic, which indicate whether the answer is correct. If the answer is incorrect, students continue to discuss the remaining answers until the correct answer is chosen. A completed hardcopy scratch card, where the correct answer is indicated by a star, is shown in Figure 2. There are two key advantages to using the scratch cards. Students obtain immediate feedback on whether their answer is right or wrong, but must continue discussions of what the right answer is even if first answer is incorrect. Often this includes important discussions about why the answer originally chosen was wrong. In addition, by collecting the scratch cards (or viewing the results electronically), the instructor can easily determine which areas students have struggled with, to tailor the *Corrective Instruction* which follows the tRAT and forms the final part of the *Readiness Assurance Process*. If all students have struggled with a specific area, more time can be spent on addressing any misconceptions. The activities described up to this point are equipping students with the core concepts required to solve the more challenging problems that form part of the *Application Activities*. These are also carried out in the same teams and, in "pure" TBL adhere to the 4S's (see Figure 1).

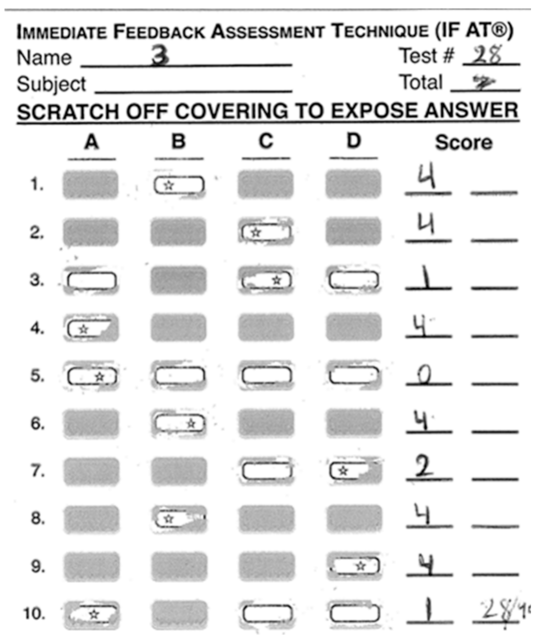

Figure 2. Example of an IF-AT (Immediate Feedback Assessment Technique) scratchcard used in the tRAT. The optional scoring system used on this card is 4, 2, 1, 0 for revealing a correct answer on the 1st, 2nd, 3rd, and 4th attempt, respectively.

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Table 2. Alignment of TBL to Key Principles of Constructivist Learning Theory

key principles of constructivist learning[36]	alignment of TBL to constructivist principles[37]
The teacher is a guide to facilitate learning.	TBL is student-centered, with instructor facilitating discussion between learners
Teaching involves providing opportunities to expose inconsistencies between learners' current understandings and new experiences therefore providing the opportunity to develop new schemes	TBL encourages learners to compare their existing understanding with peers and discuss contentious points in the tRAT and application activities, with the aim of promoting integration of information into existing schemes.
Learning should be active using relevant problems and group interaction	Application activities incorporate problems testing the specific knowledge the students should have acquired, requiring students to interact with each other to obtain the final answer.
Time is needed for reflection on new experiences	Comparison of understanding in the tRAT and application activities allows "reflection in action". Feedback from peers allows students to reflect upon their role in group learning.

In TBL students complete the in-class activities in an instructor-formed mixed ability team which remains static for the duration of the course. Completing activities within a team holds students accountable for coming to class prepared, with studies showing enhanced student preparation for class as compared to "traditional" classes.[22,23] The accountability of being part of the same team for the duration of the course can also be reinforced by the use of peer feedback. TBL is an effective active learning strategy shown to lead to an increased ability to access higher order learning outcomes,[23,25,26] and overall enhanced student learning.[27−30]

Theoretical Framework Underpinning TBL

The educational techniques used to facilitate active learning generally require students to build upon and create links between existing information frameworks to develop and extend their understanding. This aligns with constructivist learning theory which proposes that people create their own knowledge rather than simply acquire ready formed knowledge. The constructivist framework is the most widely accepted theory of how effective learning in chemistry takes place.[31,32] It is composed of two processes through which our mind adapts to incorporate and construct knowledge: assimilation and accommodation.[33] Assimilation is the formation of connections between new information and existing frameworks while accommodation is modification of the frameworks to incorporate knowledge. Constructivist theory is limited by the implication that personal knowledge is being created individually, with no explicit reference to the benefits of social interactions.[34] A more appropriate educational theory here is socio-constructivism where interaction with others and developing a common understanding are important for effective learning.[35]

Team-Based Learning comprises a sequence of structured activities which can be aligned with the key principles of constructivist learning theory (Table 2). The structure of TBL, specifically testing the core concepts via the iRAT and tRAT followed by *corrective instruction*, clearly aligns with constructivist learning theories where students need to create appropriate scaffolds to build new more complex information upon.

TBL in Chemistry

TBL has been used widely in medical and management education, but is relatively under-exploited in physical sciences and mathematics teaching. This may be due to the perception that questions in the physical sciences have either a right or wrong answer,[38] which limits the discussion intended in the application activities. However, it has been shown that TBL can be an effective strategy for teaching chemistry, mostly with minor modifications to the traditional structure. Most commonly modifications occur in the application activities, with the removal of the "specific choice" element, leaving problems open ended.[39,40] Offering a specific choice in most chemistry questions would likely limit the intended discussion, whereas leaving the problem open ended allows significant discussion of the methods to find the correct answer. A detailed description of the creation of multiple-choice questions for the *Readiness Assurance Tests*, and *Application Activities*, in chemistry TBL is provide elsewhere.[40] Metoyer et al. expanded upon the tRAT by assigning each team a specific multiple choice question, and asking them provide a rationale for the correct answer in a college-level chemistry course.[41] Departing from the traditional format, Firmino et al. used the RAP as a diagnostic tool to reveal misconceptions in core chemistry material in the chemistry module as part of a dentistry course.[42]

While traditionally, TBL is used in a flipped classroom model with content delivery taking place outside the classroom, there are examples in chemistry, where TBL has been used successfully in conjunction with lectures (i.e., with the lectures acting as the pre-class preparation), replacing traditional problem classes, in an entry level physical and analytical chemistry course[43] and a UK FHEQ 3 (equivalent to college-level) general chemistry course.[44] The disadvantage to this approach is that it limits in-class active learning as both lectures and TBL workshops need to be accommodated with the confines of the timetable.

More recently, TBL has been used as an effective form of distance learning in chemistry during the Covid-19 pandemic, in both an upper-division biochemistry course[45] and an entry level physical chemistry course.[46] Woodbury et al. suggested that, with appropriate modifications to the online environment, online TBL allowed students to gain just as much as in-person TBL classes.[45] A study into perceptions of online TBL during the Covid-19 pandemic found that TBL was perceived to be the best online teaching method experienced by both staff and students.[47] It has also been highlighted that online TBL is an effective strategy for socialization of students in an online environment.[46]

Despite the modifications to the TBL process in chemistry teaching, conclusions drawn from evaluations largely follow trends from subjects where it is used more widely (e.g., medical sciences). TBL is observed to result in improved attendance,[41,45,48] reduced attrition,[49] and to further engage students in active learning processes as compared to "traditional" teaching methods.[39,41,50] Students report an increased accountability to complete the pre-class preparation so as not to disadvantage their team.[51] In addition, Alverez-Bell et al. report that the Readiness Assurance Process and Application Activities allow general chemistry students to recognize that they can achieve higher level understanding during the collaborative process of TBL.[52] Students consistently report to find TBL an enjoyable learning experience.[43,50,53] Evidence also suggests TBL leads to enhanced student attainment.[41,43,53] It is reported

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that TBL is an effective learning strategy for potentially less motivated students across all degree levels (i.e., general chemistry students as compared to those studying medicine)[53] and less students may be "left behind" using this method.[54] TBL has been used across a range of chemistry teaching, including physical and analytical,[39,43] organic,[40,51] medicinal chemistry,[40,47] and practical chemistry,[54] although it appears to be most commonly used in general chemistry courses.[41,42,44,49,52,54,55]

As far as the author is aware, there are limited examples of in-depth qualitative analysis of student opinions of the use of TBL in chemistry. In addition, it appears that most examples of the use of TBL in chemistry are in introductory and entry-level chemistry courses, and none of the cited examples specifically refer to an inorganic chemistry course. Hence herein is described an investigation into student perceptions of the use of Team-Based Learning in a U.K. FHEQ Level 6 (equivalent to U.S. upper level) in an advanced inorganic chemistry course (transition metal electronic spectroscopy).

■ METHODOLOGY

This study aimed to address the following research question:

What are chemistry students' perceptions of Team-Based Learning as an effective active learning strategy for learning an advanced inorganic chemistry topic?

Before this project, the material in this course (transition metal electronic spectroscopy) was delivered via 6 × 1 h interactive lectures (a combination of content delivery and worked problems). It was observed that students found the topic conceptually challenging and engagement in active learning (i.e., the worked problems) in the class was poor. In general, students did not complete the worked problems but rather waited for the lecturer to go through the answers. Anecdotally there was indication that students struggled to put what they had learned into practice during the lectures and needed some time to assimilate the information. In this study, the lectures were replaced with 3 × 2 h TBL workshops, (one per week for three consecutive weeks) each preceded by ~30 min of content delivery via screencasts. A flipped pedagogy was chosen for teaching these classes since the pre-class preparation would provide the opportunity for students to study the material in advance and have the opportunity to assimilate information before the workshops. TBL was specifically chosen since the readiness assurance tests allow students to assess their knowledge of the core concepts and have any misconceptions addressed before tackling the more complex problem solving in the application activities. The researcher prepared all materials used in this intervention, with some input from summer placement students who added subtitles to the screencasts. Pre-session screencasts were made available one week in advance of the relevant session. Before the course started, students were given a short presentation outlining the rationale for using TBL to teach the course, and encouraged to self-reflect on their own contribution to the TBL workshops (the introductory materials used are provided in the Supporting Information, SI). The TBL workshops followed the standard format for TBL (iRAT, tRAT, Corrective Instruction, Application Activities). The questions that comprised the Application Activities did not adhere to all the 4S's (they were open ended questions without a *specific* answer and hence *simultaneous* reporting was not possible) but were a *significant* problem and the *same* problem for all teams, which is consistent with other studies using TBL in chemistry teaching.[39,40] The TBL workshops were run by one instructor, the academic lecturer for this course (equivalent to the course professor in the U.S.). The instructor generated mixed ability (based on grades from previous courses) teams of 5 or 6 students, which remained constant for the three workshops.

All participants in this research project were FHEQ Level 6 (equivalent to U.S. senior level) Keele University chemistry students taking the module CHE-30042, who all had some prior experience of TBL. The students had experienced TBL in two short courses (in introductory organic chemistry[40] and NMR spectroscopy[49]) in the previous years of their degree (one in each year). The first of these courses was deemed "full TBL" (i.e., in a flipped classroom model) where all lectures were replaced with a series of e-learning resources. The second course used TBL workshops alongside lectures. The module was core for students studying single honors chemistry pathways and optional for students studying combined honors chemistry pathways. All 74 students taking this module were given the opportunity to participate in this study. Ethical approval for this project was obtained through the School of Social Science and Public Policy Student Projects Ethics Committee at Keele University.

This project involved collection of data both pre- and post-intervention. The pre-intervention data was collected through a questionnaire containing open-ended questions ($N = 63$), aimed to ascertain participants existing perceptions of TBL, and used to inform the intervention. The post-intervention data was collected through a questionnaire comprising both Likert-style (based on an existing TBL questionnaire[25]) and open-ended questions ($N = 61$), and a focus group ($N = 9$). The main intention of the focus group was to provide opportunity to probe ideas that emerged from the questionnaire data. Focus groups were chosen over interviews since they allow more easily for reflection upon collaborative experiences[56] which aligns with TBL being itself collaborative.

Both pre- and post-intervention questionnaires were deployed during in-person classes. The focus group used a nonprobability volunteer sample selection[56] and carried out in person by a facilitator not involved in the research project to allow participants to express their opinions freely since the researcher was also the person delivering the teaching intervention. The focus group was semi-structured, using a selection of pre-determined questions, (SI) with additional questions or requests for clarification or elaboration emerging during discussions.[57] The focus group was audio and video recorded, then transcribed by the researcher.

The data collected through the open-ended questionnaire data both pre- and post-intervention, alongside the focus group data, were analyzed using thematic analysis using the method reported by Bree and Gallagher,[58] based on the analysis method described by Brenner.[59] Thematic analysis was chosen since it allows flexibility and provides a rich and detailed account of the data.[60,61] A theme captures an important aspect of the data, relevant to the research question, regardless of the frequency with which it occurs within the data. However, it should be noted that the quotes provided to evidence the emergent themes and subthemes are illustrative, and none of the themes or subthemes discussed arise from a singular item of data. Thematic analysis was completed by the researcher and verified by a second independent person. The Likert-style data collected post-intervention was used to ascertain relative strength of opinion.

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Table 3. Themes Raised by Students in Pre- and Post-Intervention Questionnaire and Post-Intervention Focus Groups

themes	positive/ negative/mixed	illustrative quotes
preparation		
incentive to complete preparatory work	*positive*	*"forces to do work before session otherwise you have no idea what is going on"*
	negative	*maybe make them partially graded to encourage work beforehand*
building upon prior knowledge	*positive*	*"you get more out of it because you have previous knowledge"*
		"You should go to the session with knowledge of the subject so can apply it in a different way"
passive pre-class materials—request for worked problems	*mixed*	*"I wish that the screencasts for week 1 had more practice questions. No one in my group understood the concepts which makes it a bit pointless"*
		"Watching screencasts are passive - would be better to do a question alongside"
		"the screencast that encouraged you to pause and calculate the answers was very helpful"
collaboration		
increased understanding through explanation/ discussion/debate with peers	*positive*	*"discussion with a large group and analysing whose answer is correct and why is a much better way of retaining knowledge"*
		"Being able to explain to someone else your reasoning for your answer helps reinforce knowledge"
		"you can see how other people approach understanding"
disengaged/poorly prepared team members	*negative*	*"People who do not prepare beforehand do not fully engage"*
team composition	*mixed*	*"choose our own groups"*
		"important to get to know your group so you are comfortable/confident with them, and whether you feel comfortable debating with them"
		"better to have a mix of abilities - if everyone is struggling, no-one can explain it"
application		
effective for problem solving	*positive*	*"very effective teaching method for···parts···which focus on problem solving"*
mcqs are ineffective for exam revision	*mixed*	*"multiple choice is less preparation for exam style questions"*
		'it helps when···converted [MCQs] to what they'd be as exam questions afterward"
tbl structure		
more structured/retain focus	*positive*	*"more structured environment with scheduled time for individual and group work"*
		"Remain more focussed as constantly using our brain throughout all of the session"
instant feedback	*positive*	*"You can see where you went wrong and get the correct answer straight away"*
		"You get immediate feedback and it definitely helps with learning"
unable to work at own pace	*negative*	*"you don't get to answer questions at your own pace which sometimes means you still don't understand"*
role of instructor		
answering questions/challenging misconceptions	*positive*	*"they help if the group becomes stuck and can listen out for discussions and intervene if you're going in the wrong direction"*
		"explanation of people's answers at the end of the session are very useful because they can reveal places where it's easy to make a mistake"
limited access to instructor in tbl workshop	*negative*	*"more supervisors where possible? Sometimes you're stuck and sit wasting time"*
		"if you don't understand, difficult to ask for help"
comparison with lectures		
topic difficult to learn via lectures (problem solving/ lack of preparation)	*positive*	*"would have been really difficult to learn just via lectures* as it is a *problem-solving topic"*
		"No-one bothers with pre-reading for a lecture"
		"Usually I come to lecture unprepared, with only the slides printed off"
more effective in conjunction with lectures	*negative*	*"TBL to build upon lectures rather than replace them completely"*
		"potentially useful to have a summary lecture after all the TBL sessions"
		'If the topics were quickly recapped before starting the session then I would be able to answer more questions'
inadequate revision material	*negative*	*"you don't get a good set of notes to revise from later"*

■ RESULTS AND DISCUSSION

Upon analysis, the same major themes were emergent from both pre- and post-intervention questionnaires, and focus group, and hence they are discussed collectively. Table 3 shows the key themes with subthemes provided with illustrative student quotes. Three of the emergent themes; *Preparation*; *Application* and *Collaboration*, map onto four out of five of Michael's key aspects of active learning (Table 1).[3] Being prepared for class and hence being able to build upon prior knowledge is a constructivist principle,[37] while the application of this knowledge is required for problem solving. The *Collaboration* theme also encompasses *Knowledge Articulation* as explanations are provided and gained to and from peers. This indicates that (perhaps unsurprisingly given that TBL is an established active learning strategy) these students strongly associate TBL with being an active learning experience. There is no clear link to Michael's final principle of active learning, *Knowledge Transfer*. This may be the result of this study being confined to a short course within a single module, so students did not consider this aspect. Alternatively, it may be a modular system can prevent students from thinking about chemistry in a holistic manner, and this is certainly worth further investigation. Two further themes linked strongly to an effective active learning environment; the *TBL Structure* allows active learning to take place, and the *Role of the Instructor* is to facilitate this. The final theme focused on *Comparison with Lectures*.

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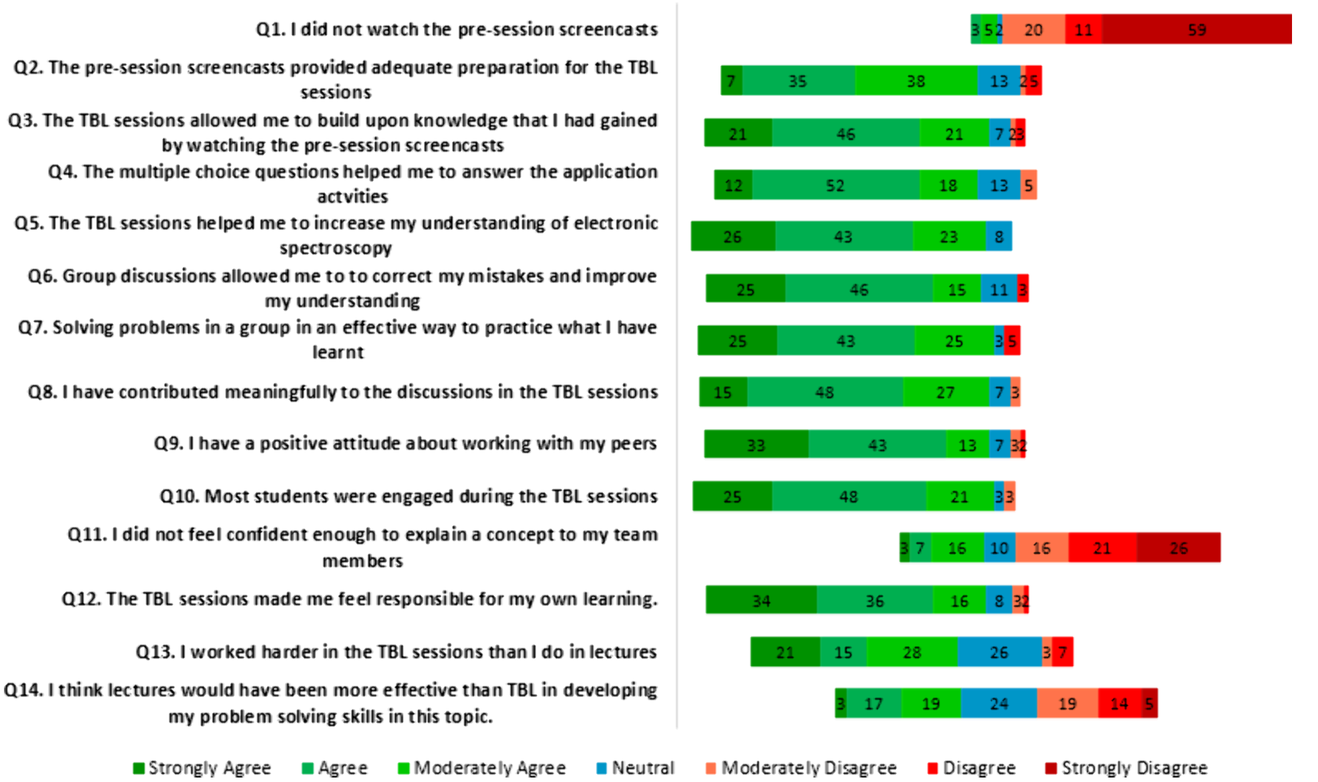

Figure 3. Histogram of responses (%) from the post-intervention Likert-style questionnaire (N = 61).

Figure 3 shows results from the post-intervention Likert-style questionnaire, which are discussed alongside relevant themes below. The questionnaire is available in the SI.

Preparation

Subthemes in the *Preparation* theme focused on the incentive to complete the preparatory work, the advantages of building upon the preparatory work in the TBL workshops in advance of the TBL workshops and the perceived passive learning from the screencasts provided. While the reasoning behind students feeling compelled to complete the preparatory work is not explicit, it is likely due to them feeling accountable to their team in the tRAT, and do not want to appear to be the person who has failed to prepare.[61] Although the majority of this class claimed to have engaged with the preparatory materials (as determined from the answer to Q1 in Figure 3), a common complaint was about students who were not prepared for class. A suggested mitigation was to grade the preparatory work, for example using a quiz, which has been used in examples of the flipped classroom in chemistry.[12,13,17,19,20] Another suggested mitigation is to assign marks to the in-class activities to ensure pre-class preparation has taken place.[15,16] However, there are reports of this being unpopular,[40] especially given the conceptually challenging nature of the topic and high stakes nature of final year assessment.

There was agreement (80%) from post-intervention Likert questionnaire data that the screencasts provided adequate preparation for the workshops (Q2). However, there were concerns over the extent of preparedness due to lacking understanding of the screencast content. Related to this, a strong subtheme was the need to incorporate worked problems within the screencasts to assist understanding. Incidentally one of the screencasts did contain such a problem, which was commended by students. The focus, in the design and preparation of the screencasts, was content delivery, since the active learning was intended to take place in the TBL workshop. However, clearly, a pre-class active learning experience is also important to allow students to appropriate scaffold information to build upon in the TBL workshop.[10,62,63]

It is interesting that there was no explicit mention of the effort required outside class to prepare for the TBL sessions, either pre- or post-intervention, which has been highlighted as an issue in other flipped classrooms.[15,64] It should be noted that the examples cited refer to high-school and entry-level students hence the students in this study may be more highly motivated to complete pre-class work at the upper-level of their degree.

Collaboration

Questions related to the collaborative aspect of TBL (Q6−9) were answered positively in the Likert questionnaire. Clearly collaboration constitutes both the best aspect of TBL, but also the worst, when team members are not engaged. Discussion and debate were highlighted as perceived advantages of collaborative learning. The value of different team members providing alternative modes of thinking also featured. Peltier et al. also referred to teamwork as being important to introduce the different learning styles used by peers.[65] While many responses cited learning from their peers, students also recognized the importance of articulating explanations to others. Lockspeiser et al. have found that students who acted as peer teachers recognized improvements in their own learning.[66] The Likert questionnaire (Q11) revealed that the majority of students felt confident explaining a concept to a peer, although there is a significant number of students (26%) who did not. This warrants further consideration, especially considering that there is evidence that students from marginalized groups may find team work to be exclusionary.[67]

The majority of collaborative learning complaints related to issues with individual team members, with "social loafing" featuring prominently. An interesting emergent subtheme related to ways to ensure team members are not disadvantaged by poorly engaged team members. The two main suggestions were to allow students to choose their own teams or to frequently change team composition. The first suggestion of groups being self-selected was counteracted with the point that if students picked their own groups a mixed ability group could not be guaranteed which may lead to students comprised of lower ability students struggling. Similarly, students in Donnelly and Hernandez's study commented that having high achieving students working together does not provide opportunity for them to share their knowledge with peers.[68] Henning et al. advise against self-selected groups as it may lead to anxiety in certain groups of students.[69]

With regard to the second suggestion, reassigning groups weekly has been recommended by to alleviate personnel issues with group work.[68] These ideas were the subject of much debate in the focus group. With regard to the first point about changing the teams weekly, this suggestion was contested with the point that it is necessary to become familiar with team members to become confident in sharing answers. Indeed Capel et al. reported the importance students placed on being "close" with their team.[40] The final consensus from the focus group participants was that, for this course, "*3 weeks [is] not long enough to change groups*". It is interesting that, upon discussion, the students have come to the same conclusions about team composition as is championed in the TBL literature: teams should have a diverse composition and remain together for the duration of the course to "*promote optimal team performance*".[70] This provides justification for the use of focus groups as a data collection tool, in terms of students questioning each other and arriving at a more meaningful conclusion.[70]

Application

The effectiveness of TBL for topics that involve problem solving was commented upon, which is consistent with student perceptions in a study by McCubbins.[26] The Likert questionnaire data (Q5) also agreed that the TBL sessions allowed students to increase their understanding of electronic spectroscopy. However, the most valuable finding from the pre-intervention questionnaire date related to a key element of TBL—the multiple choice questions (MCQs). It was suggested that MCQs did not offer appropriate preparation for the open-ended questions in written exams. The MCQs had limited use after the TBL workshop since they did not align with the final assessment. As a result of this pre-intervention feedback the MCQs were converted to open-ended questions to aid revision, which was unanimously praised by all focus group participants. An example of how a selection of MCQs were converted to open-ended questions for exam revision is provided in the SI.

TBL Structure

A key difference between TBL and other active learning strategies is the specific structure of the workshops including the iRAT, tRAT, and application activities. Students have identified that they are more productive as a result of the greater structure, retaining focus more readily than in equivalent unstructured problem classes, as evidenced by the illustrative quotes in Table 3. This is consistent with anecdotal instructor observations from unstructured problem classes where students might complete 20−30 min of meaningful work before becoming distracted. From the Likert questionnaire results (Q3), 88% of students agreed that the TBL sessions allowed knowledge that had been acquired during the pre-class preparation to be built upon, and 82% of students agreed that the MCQs helped them to answers the application activities (Q4). Testing the core concepts via TBL before moving onto problem solving in the application activities is a key aspect of TBL.[70]

Another aspect of the TBL structure identified is the use of IF-AT scratch cards[24] for immediate feedback. A commonly cited issue is a lack of engagement in feedback,[71,72] with Gibbs & Simpson stating that this is likely to be greater if it is received by students "*while it still matters to them*".[72,73] Certainly, this applies to the instant feedback received during TBL workshops where the students are still thinking about the questions they are receiving the feedback upon. Without this process of immediate feedback, they might have left the workshop before realizing that their answer was incorrect; misconceptions can be addressed in a timelier manner.

Role of the Instructor

Despite TBL being a collaborative learning experience, the importance of effective facilitation by the instructor was emphasized in terms of circulating the room to answer questions, question reasoning, and challenge misconceptions. These points were also highlighted by Kelly[74] and Rotgans[75] in their study of the "inner workings" of TBL. In addition, Kelly found that there were reasonably high levels of interaction between the learner and instructor.[74] Despite this, it has been queried as to why students believed the instructor to have such a positive effect on learning since they suggest the significant guidance provided by the structured activities reduce the role of the instructor to just needing to provide minor clarifications rather than substantial content delivery.[75]

Some students expressed concern that there was less access to instructors to ask questions in TBL workshops compared to standard problem classes. One of the cited advantages of TBL is that you can run classes for large cohorts with very few instructors required.[76] However, one instructor can only function effectively in TBL workshops with a certain number of teams. It is recommended a cap is placed on the number of students per tutor so that all students feel they have adequate access. A ratio of one tutor per 72 students (equivalent to approximately one tutor per 12 groups of 6) is certainly very manageable. Going beyond one tutor per 15 groups is likely to negatively impact student experience.

While it is vital that instructors play an active role in the workshop, it is also important to manage students' expectations with regard to collaborative learning strategies since they may feel they are entitled to instructor explanation, and that of their peers is inferior.

Comparison with Lectures

A strong theme emergent from the post-intervention questionnaire data was student preference for lectures. There were various suggestions for the quantity and type of lecture, either a full lecture course or pre-/post-TBL summary lectures. The approach of using a summary lecture at the beginning of a workshop has been used been used in examples of the flipped chemistry classroom.[10,17,20]

Interestingly it was commented that the lack of lectures meant they did not have appropriate notes to revise from later. This is a point of perception, since the lecture notes previously used for this topic were all provided, only segmented into the relevant notes for each screencast. Students experiencing TBL might feel "cheated" out of gaining more knowledge.[77] In Yeung's experience of flipping the chemistry classroom, they also found that students preferred gaining information in a lecture.[16] This may be because lectures are familiar and students struggle with adapting to a completely active learning model.[78]

The focus group was used to further explore the desire for lectures and although similar opinions emerged, the focus group attendees did concede that the problem-solving nature of the electronic spectroscopy topic would have made it difficult to learn via lectures. Mooring et al. reported student feedback on chemistry classroom flipping stating "*every challenging class should have this method*".[21] Interestingly a lot of the reasons cited as to why lectures would have been less effective than TBL refer to a lack of incentive to prepare for lectures as compared to the TBL workshops.

The Likert questionnaire data (Q13) shows that a majority (64%) of students believe that they work harder in TBL workshops than lectures. However, contradicting the qualitative data obtained, opinion is completely divided about whether TBL workshops enhance problem solving skills as compared to lectures (Q14). It is possible their preference for lectures has influenced the answer to Q8. It is likely that students know active learning strategies are better for learning, but also require more effort,[79] and hence they may not want to be engaged in these strategies all the time.

Deslauriers reported student preference for lectures over active learning strategies and recommends that instructors need to explicitly present the value of active learning strategies for learning from the outset.[80] It has been suggested that students with prior experience of lectures are less likely to have a positive perception of TBL compared with students who are only familiar with TBL on a particular course.[81,82] Students in this study were familiar with TBL but typically had been taught via lectures during their degree program, which is what they might have perceived as the "normal" way of being taught.

■ LIMITATIONS, CONCLUSIONS, AND IMPLICATIONS

The main limitation of this study is that the data has been collected from a single cohort in the third year of their degree. However, key findings do align with studies relating to both team-based learning and classroom flipping in chemistry teaching. Since students had already experienced two years of university before taking part in this project, it is unclear whether they perceived "lectures" to be the "normal" university experience. Going forward, it is of interest as to whether chemistry students with no prior experience of content delivery via lectures at university level would have the same perceptions of using TBL to replace lectures. It should be noted that data collection in this study occurred prior to the Covid-19 pandemic and hence students who experienced the range of teaching techniques during the pandemic may have different perceptions of lectures as a necessity. In addition, students currently in the latter stages of their degrees who have studied during the pandemic may be fatigued from online learning[12] and may respond differently to being asked to complete pre-class preparation online. Since this study investigates a single cohort of students, assessment data has not been examined. However, going forward, it would be of interest to ascertain whether the attainment gains seen in entry level classes[41,43,53] are replicated in advanced level classes.

Results from this study indicate that advanced level chemistry students strongly associate TBL with being an effective active learning experience, and overall a positive learning environment. They placed high value on having incentive to interact with the pre-class materials, and hence arriving prepared for the classes. The structured nature of TBL allowing core concepts to be assessed before the application of these concepts to more challenging problem-solving activities was praised, alongside having the opportunity to discuss and learn from peers. Many of the criticisms of TBL related to unprepared and disengaged team members, which is a perennial issue with any team work, not exclusive to TBL. Having some negative experiences of team work, and learning strategies to cope with this, is an important employability skill, hence it is certainly no reason to halt this type of activity. It is important that students develop strategies to manage the issues that arise in collaborative learning experiences as they occur. It is recommended that instructors include implicit information about effective team working skills, including (where time permits) a dedicated session on team working skills. Nardo et al. emphasize the importance of group work guidelines in creating an inclusive learning environment to ensure an equitable active learning experience for students from marginalized backgrounds.[67] Woodbury et al. attempt to address this by asking students to each identify one "constructive" behavior (a strength) and one "destructive" behavior (an area for improvement) from a predetermined list. These form part of a pre-TBL team discussion about how the team is going to be successful.[45] Using peer to peer feedback can also be effective in longer TBL courses to allow students to improve their team working skills.[83]

Despite, TBL being a collaborative learning experience, students place high value on the role the instructor plays in terms of circulating the class to answer questions and challenge misconceptions, rather than merely act as a facilitator. Although a key advantage of TBL is that only a single instructor is required for a large cohort, it is recommended that one instructor does not manage a cohort with more than 15 teams (equivalent to 100−120 students with teams of 5−6). Of course, a larger class could be managed with two or more instructors.

Some important, and easily addressed issues were raised relating to the content of the pre-class screencasts and the materials provide for consolidation/revision purposes after the classes. Requests were made for more interactive screencasts that involved worked problems to assess understanding, and hence make the pre-class preparation a less passive experience. Focus should be directed toward ensuring pre-class preparation is an active learning experience as well as the in-person class. Aside from the inclusion of worked problems, it has recently been shown that use of an online social annotation platform allowing students to discuss pre-class material has been effective in a flipped chemistry classroom.[84] It was also noted that, despite their effectiveness within the TBL workshop itself, MCQs do not align with what the students are expected to do in summative assessment in this course. Conversion of MCQs to open-ended questions for revision purposes was highlighted as being very useful. It is recommended that instructors ensure materials provided are aligned with summative assessment and, post-class, are provided in a format that allows students to effectively prepare for their assessment.

Despite the positive feedback for TBL as an active learning experience, and the recognition that having lectures would result in less pre-class preparation, and diminished problem-solving activities, a large majority of students requested the lectures were reinstated. Consistent with other studies into student perceptions of both TBL and other flipped classroom activities, it is apparent that students recognize active learning strategies

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are better for them, but are not prepared for lectures to be removed altogether.[80,81] There seems inherent belief that lectures are the best way for content to be delivered and they are missing out on a key aspect of their education without lectures. It is possible that as more courses are adapted to the flipped model, the importance placed on lectures is diminished and this certainly warrants further investigation.

While TBL is relatively underused in chemistry teaching, especially compared to medical and management sciences, students perceive that it is an effective active learning strategy to teach advanced chemistry topics. It is recommended that chemistry educators wanting a structured method to enhance active learning in their classroom consider introducing Team-Based Learning into their teaching.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00655.

Copy of slides for pre-TBL course presentation/self-reflection questions to students; example RAT and application activity questions/answers/commentary; example of RAT questions converted to open-ended question/commentary; pre-intervention questionnaire; post-intervention questionnaire; Likert questionnaire full results; and focus group questions (PDF)

Copy of slides for pre-TBL course presentation/self-reflection questions to students; example RAT and application activity questions/answers/commentary; example of RAT questions converted to open-ended question/commentary; pre-intervention questionnaire; post-intervention questionnaire; Likert questionnaire full results; and focus group questions (DOCX)

■ AUTHOR INFORMATION

Corresponding Author

Laura M. Hancock − *School of Chemistry, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom; School of Chemical and Physical Sciences, Keele University, Keele, Staffordshire ST5 5BG, United Kingdom;* orcid.org/0000-0003-0417-2013; Email: l.hancock@bham.ac.uk

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.3c00655

Notes

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