Partanen, Lauri J.

A Guided Inquiry Learning Design for a Large-Scale Chemical Thermodynamics Laboratory Module

Published in:
Journal of Chemical Education

DOI:
10.1021/acs.jchemed.2c00387

Published: 10/01/2023

Document Version
Publisher's PDF, also known as Version of record

JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc Article

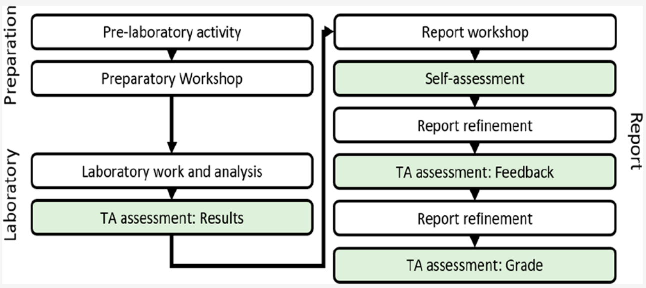
A Guided Inquiry Learning Design for a Large-Scale Chemical Thermodynamics Laboratory Module

Lauri J. Partanen*

Cite This: *J. Chem. Educ.* 2023, 100, 118–124 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: In this action research study, I propose a guided inquiry alternative to the traditional physical chemistry laboratory module where the equilibrium constant of acetic acid is determined conductometrically. I complement the guided inquiry structure with a 360° feedback support framework for the preparation and assessment of a laboratory report. The new laboratory module showed great promise, improving both report marks and student experiences. Diligent training of teaching assistants, ample availability of formative feedback, and reservation of sufficient time for the guided inquiry activities were identified as key contributors for the success of the module.



KEYWORDS: *Physical Chemistry, Laboratory Instruction, Inquiry-Based, Discovery Learning, Second-Year Undergraduate, Conductivity*

■ INTRODUCTION

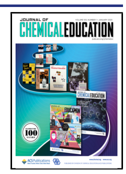
In traditional expository laboratory teaching, the teacher provides explicit instructions that detail the experiments and observations students are supposed to make. The students then follow these instructions step-by-step toward a predetermined outcome.[1] The focus of this cookbook style of instruction is on facts, concepts, scientific terminology, and the verification of existing results rather than knowledge and prior experiences.[2] The upside is that the time-effective nature of the traditional laboratory enables more experiments to be carried out. The downside is that the students often struggle to develop higher order thinking skills, obtain procedural knowledge, and learn effectively. Therefore, alternatives like inquiry-based learning have been increasing in popularity over the last few decades, as these approaches show improved learning gains and focus on process skills.[3]

Inquiry-based learning can be divided into three levels with respect to the amount of structure provided for the student.[4] At one extreme is structured inquiry, where the teacher crafts the research questions and the processes. This is followed by guided inquiry, where the teacher provides the research question and the students construct the solution process. Meanwhile, in open inquiry students develop both their own questions and procedures without knowing what results to expect prior to the investigation. This places high demands on student expertise.[5] Consequently, many teachers feel that students in the early stages of their studies are not prepared for learning through open inquiry.[6] Furthermore, students themselves show more positive attitudes toward guided inquiry and feel that it better benefits their learning.[7]

One promising implementation of guided inquiry is Process Oriented Guided Inquiry Learning (POGIL). In POGIL, the learning cycle revolves around critical thinking questions and is subdivided into three steps: Exploration (answering directed questions), Concept Invention (constructing an idea), and Application (applying the idea to a new context).[8] POGIL has been associated with increased learning gains compared to more traditional modes of teaching and generally positive student experiences.[8−10] Consequently, it has served as the theoretical foundation for several innovative laboratory modules in chemistry.[11−14]

Physical chemistry connects chemical phenomena with the underlying physical and mathematical principles. It is thus fundamental for a deep understanding of chemistry. This poses challenges for students as they need to synthesize concepts across physics, mathematics, and chemistry[11] and learn how to describe chemical phenomena through equations. In this action research study, I propose a POGIL-inspired guided inquiry alternative to the traditional physical chemistry laboratory module where the equilibrium constant of acetic acid is determined through conductometry. Since students often struggle reporting their results, I complement the guided inquiry structure with a support framework for the preparation and assessment of a laboratory report. This framework is based on

Received: April 17, 2022
Revised: September 21, 2022
Published: November 1, 2022



https://doi.org/10.1021/acs.jchemed.2c00387
J. Chem. Educ. 2023, 100, 118–124

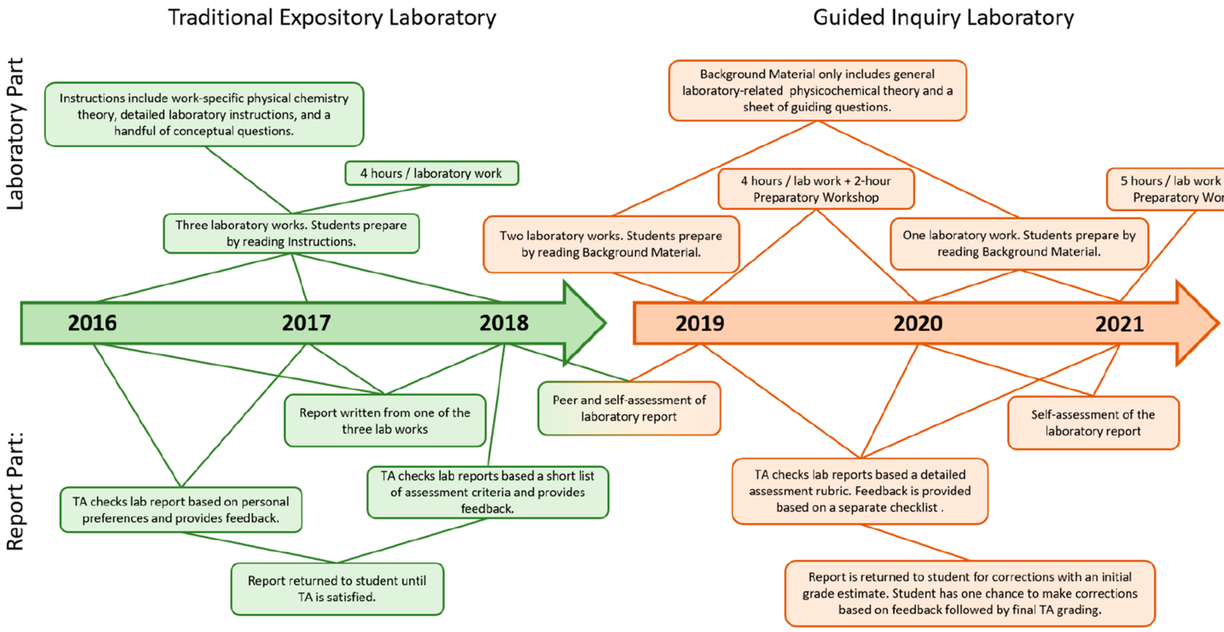


Figure 1. Development of the guided inquiry laboratory module.

Table 1. Number of Laboratory Work Participants between Different Years and the Mean Marks from the Laboratory Report[a]

	2016	2017	2018	2019	2020	2021
N	117	140	108	128	154	123
mean (sd)	4.76 (2.95)	5.90 (3.21)	6.12 (2.87)	6.93 (2.26)	6.92 (2.16)	6.54 (3.13)

[a]All marks have been scaled to the range 0−10.

the 360° feedback model by Tee and Pervaiz[15] where the aim is to construct a holistic framework of formative assessment to enhance students' learning. The six core elements of the 360° model are feedback quantity, quality, timing, communication, ability to promote reflection, and social pressure exerted by peers in an environment dominated by positive social interdependence. The efficacy of the new laboratory module is assessed through quantitative measures of learning and both quantitative and qualitative measures of student experiences.

■ METHODS

Course Background

All data was collected from a Chemical Thermodynamics course at Aalto University in the period 2016−2021. Chemical Thermodynamics is a second-year 5 ECTS BSc-level course that runs from September to December. The number of participants is between 100−150, and one ECTS credit corresponds to 27 h of work. The course includes obligatory laboratory teaching in addition to tasks like lectures, exams, and various exercises. The laboratory teaching is organized during an intensive period from October to November when most of the other activities of this course are halted. Students write a report on one of the laboratory modules. This is their first individual full-length report during the BSc studies. Together, the laboratory teaching and the report contribute around 10−20% toward the course grade.

Following literature recommendations,[16] the transition from traditional cookbook laboratories to guided inquiry occurred incrementally from 2019 onward, as shown in Figure 1. From 2016 to 2018, three laboratory modules were included: "The spectrophotometric determination of the equilibrium constant of a pH-indicator", "The determination of the solution enthalpy of potassium chloride", and "The conductometric determination of the equilibrium constant of acetic acid." To provide sufficient time for the guided inquiry laboratories, the first of these was dropped in 2019, and the two remaining ones were redesigned. The solution enthalpy module was further discarded in 2020 due to the COVID-19 pandemic.

Data Collection

Assessment data from the laboratory report was gathered for all years. Once the development activities started in 2019, laboratory related feedback was also collected through a separate online feedback form at the end of course. This feedback form was part of a weekly exercise set.

From 2019 to 2021, the feedback form included a 5-point Likert question related to the laboratory activities: "The way that the laboratory work was organized supported my learning." From 2020 onward, this question was complimented with an open response field "Open feedback on the laboratory work/report". The feedback form also included questions that were not part of this study. The relevant parts are shown in Appendix 1 of the Supporting Information.

Participants

A total of 770 students participated in laboratory teaching. Here, participation implies that the student attended the laboratories and submitted at least one version of the laboratory report. The distribution of these students between different years is provided in Table 1. For the post-intervention cohorts, 110 of 128 (86%) provided research permission in 2019. The corresponding numbers were 122 of 154 (79%) in 2020 and 106 of 123 (86%) in 2021. Of the 2019−2021 group, approximately half (55%) of the participants were females. The mean age was 21.6, with a

https://doi.org/10.1021/acs.jchemed.2c00387
J. Chem. Educ. 2023, 100, 118−124

range of 19−43 years. Most (79%) were second-year BSc students.

Analysis

A one-way ANOVA was used to investigate the differences between the mean report marks and student responses to the Likert question in different years. For the Likert question, the results were also verified using the Kruskal−Wallis nonparametric test. To understand which differences were statistically significant, I used Dunnett's T3 pairwise comparison procedure, as recommended by Sauder and DeMars.[17] The data analysis was conducted using the SPSS software.

Abductive content analysis[18] was used for the open responses. The responses were read through by the author and an independent expert in university pedagogy to identify common characteristics. Whenever a characteristic was recognized that text segment was coded and the segments showing similar characteristics were grouped. Some responses included multiple characteristics. The responses were further characterized into neutral, positive, negative, or both positive and negative. The inter-rater agreement between these characterizations was 88%. The cases where the author and the independent expert disagreed were discussed until a common classification emerged.

Ethics of Action Research

This study followed the action research methodology[19] where the author functioned as the principal researcher, and the responsible teacher during 2019−2021, and supporting teacher in 2018. Unfortunately, this dual role poses a threat to the validity of the data.[20] To mitigate this issue, laboratory reports were mostly marked by teaching assistants (TAs). For 2016−2018, the author did not participate at all in the marking, whereas from 2019 to 2021, he was responsible for approximately 20% of the markings. In all years, the responsible teacher offered support for the TA assessment and from 2018 onward provided supporting documents such as assessment rubrics.

This study was conducted in collaboration with the university pedagogical experts both at Aalto University and University of Helsinki as part of a larger research initiative. This ensured institutional oversight. Students provided research permission at the beginning of the course starting from 2019. Information about the initiative was available on the course platform. Students were also informed of their right to renege research permission at any time with no detrimental effects on course performance. Meanwhile, only the average laboratory report score was used for the 2016−2018 cohorts who were not explicitly asked for research permission.

■ MODULE DESCRIPTION

Laboratory Work

Following the adoption of the guided inquiry framework, the laboratory workday was divided into the two parts shown in Figure 2: Preparation and Laboratory. A step-by-step guide of the laboratory day is provided in Appendix 2 of the Supporting Information. Considering the importance of prelaboratory activities for learning,[21] students were instructed to study the Background Material by themselves before participating in the Preparatory Workshop. The material was designed to review relevant general principles, such as how to calculate the equilibrium constant from the activities. It did not contain instructions on what the students would do in the laboratory.

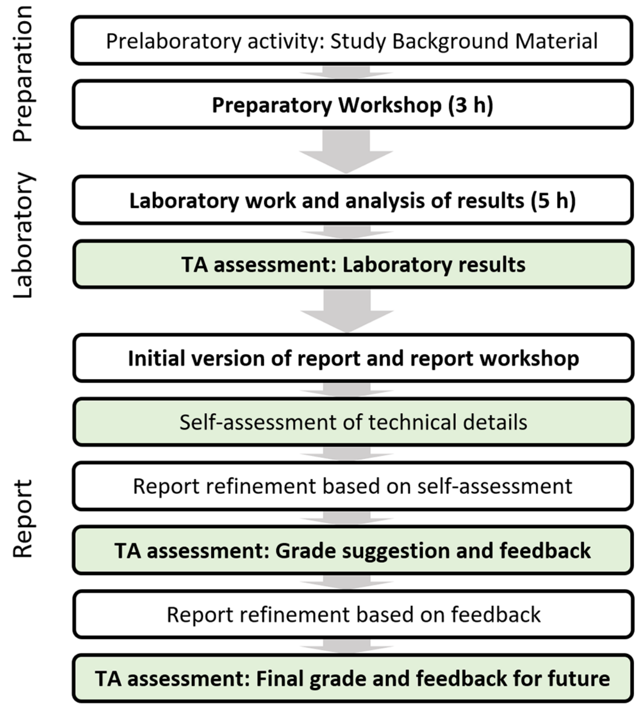


Figure 2. Outline of the laboratory module. Assessment milestones for the laboratory report are highlighted with green, whereas points where TA feedback was available are in bold.

The Background Material file is provided in Appendix 3 of the Supporting Information.

At the start of each workshop, students were given a Guidance Sheet. As shown in Appendix 4 of the Supporting Information, the sheet started with a general research question, a short introduction, and a list of equipment and chemicals available in the laboratory. This was followed by questions designed to help students come up with the laboratory experiments to solve the research question. Students worked through the questions collaborating in pairs throughout the 3 h workshop with support from the TA. At preset points, there were discussions among the whole workshop, so pairs could benefit from the insights of others. Each workshop had approximately eight students.

The Guidance Sheet included conceptual questions introducing the underlying physicochemical phenomena, theoretical questions where students derived pertinent equations from general principles, and practical questions that supported the development of a rigorous experimental routine. The first two question categories were designed to facilitate exploration, whereas the last category aimed at supporting the Concept Invention phase of POGIL.[8] Toward the end of the workshop, students wrote a detailed laboratory plan including the measured quantities and their amounts. The TAs then checked these plans before students proceeded to the Laboratory part. Accordingly, while the measuring instruments and chemicals were predetermined, students had autonomy over the measurement details like how much chemicals they used, and how many measurements they did. As autonomy is one of the key constituents of intrinsic motivation,[22] this shift in the locus of control from the teacher toward the student should positively impact motivation.

After planning the laboratory work in the Preparatory Workshop, the student pairs performed their measurements in the laboratory. About half of the laboratory time was allocated

https://doi.org/10.1021/acs.jchemed.2c00387
J. Chem. Educ. 2023, 100, 118−124

for the analysis of the results. The Laboratory part corresponded to the Application phase of POGIL.[8] Autonomous work was encouraged, even though a TA was constantly present. This was done by letting students solve practical problems during their experiments themselves, and by letting them learn how to use the laboratory equipment independently through simple instruction sheets. Ample time was also reserved for making mistakes and learning from them so that even student groups who had to redo several of their solutions typically managed to finish the laboratory work within the allotted time.

Laboratory Report

Several assessment milestones were set for the students to help them write their reports. These milestones are highlighted in green in Figure 2. First, the students worked in pairs to analyze the results at the end of the laboratory, which created positive social pressure for both students to contribute so that they could leave the laboratory in a timely fashion. Meanwhile, the TA was present throughout this process to provide timely and high-quality feedback. The analysis section of the laboratory concluded with the TA checking the students' results, so that they need not worry about the correctness of their calculations when writing the report. In the 360° framework,[15] the laboratory part thus contributed to the timing, social pressure, and quality aspects of feedback.

The second milestone pertained to the reflection part of the 360° model. It consisted of self-assessment of technical details, where students checked things like the referencing style and correct presentation of tables and figures against an assessment rubric. The rubric also included content elements to ensure that the reports contained key equations, tables, and figures. Detailed instructions on how to write the laboratory report and the self-assessment rubric were available before participation in self-assessment. The students were also encouraged to collaborate with their lab pair throughout the writing process.

A 2 h report workshop was organized a few days prior to the self-assessment deadline to provide students with more high-quality feedback in a timely fashion. At this point, students were familiar with the assessment rubric and writing instructions, which allowed for a dialogue between student and TA on what was required for the report. This workshop thus contributed also to the communication aspect of the 360° feedback.[15]

Students were instructed to revise their reports based on the automated feedback from the self-assessment rubric. Following revisions, students submitted their report for TA assessment in the third assessment milestone. In 2021, the TA read the report, provided feedback based on detailed assessment guidelines, and suggested a mark. The mark was based on a more general assessment rubric that was also accessible to the students. This rubric can be found in Appendix 5 of the Supporting Information. After the TA feedback, the students had 1 week to correct and improve their report. This was followed by a final assessment milestone where the TA marked the report based on the assessment rubric. In sum, multiple opportunities of formative feedback were provided throughout the report writing process to ensure not only the quality but also the quantity of available feedback.[15]

TA Training

The TAs played a vital role in the success of this laboratory module, serving as facilitators of student collaboration and knowledge building during the preparation and laboratory parts, and as key sources of formative feedback during the report part. Consequently, the TAs received approximately 18 h of guided instruction. The main goal was for them to learn not just what to teach but also the how and the why.[16] The training included 2 h of general pedagogical instruction with TAs from other courses, 6 h of subject and guided inquiry instruction, during which the TAs performed the workshop and laboratory segments themselves, 2 h of report grading instruction, and a minimum of 8 h of practical teaching observation where pedagogical issues were also discussed. There were additionally several hours of individual preparation, where the TAs studied the grading instructions, rubrics, and read additional material related to the laboratory topics.

Throughout their training, the TAs were taught not to provide ready solutions, but to facilitate discovery by giving out hints, and if measurements did not work out, to provide support and help students reflect on their mistakes. The role of emotions in teaching and learning were also frequently discussed, as evidenced by the materials used for the pedagogical training of teaching assistants provided in Appendix 6 of the Supporting Information. The TAs were also encouraged to roam the laboratory, asking students how they were doing and what kinds of issues they had run into. For support, both TAs and students received a second Guidance Sheet that included discussion questions for the Laboratory part. It is shown in Appendix 7 of the Supporting Information. Meanwhile, sample solutions for both Guidance Sheets can be found in Appendix 8.

Overview of the Changes to the Laboratory Module

While the general structure of the lab work stayed the same from 2019 to 2021, several small adjustments were made based on previous years' experiences, as indicated in Figure 1. For example, the Preparatory Workshop and laboratory were originally 1 h shorter from 2019 to 2020. However, in this arrangement it felt like the teacher had to provide too many ready-made solutions and there was insufficient time for students to think and discover themselves. The report was also both peer and self-assessed for the technical details from 2018 to 2019. This was changed to just self-assessment to reduce student workload and because many felt that the peer assessment enabled plagiarization of diligently crafted reports.

The 2019−2021 practices were in stark contrast to the 2016−2018 ones, as shown in Figure 1. First, there were three laboratory modules with cookbook-style instructions and no Preparatory Workshops from 2016 to 2018. The total lab time was also only 4 h, which often meant that the TA had to dish out answers to get the students to finish on time. As between 2019−2021, the students prepared a single report, but the laboratory module for the report varied from student to student. This, combined with the lack of general guidelines for marking and feedback, resulted in a highly subjective assessment process. Therefore, general guidelines for the TA assessment were provided already in 2018, but these guidelines became increasingly detailed through 2019−2021.

RESULTS

Changes in Report Scores

The means, standard deviations, and numbers of participants for each year are listed in Table 1. The different grading scales from 2016−2018 were rescaled to the 2019−2021 one of 0−10. The 2016 and 2017 courses originally employed a scale of 0−3 while the 2018 course used a scale of 0−12.

A one-way ANOVA indicated a significant difference with $F(5,768) = 10.86$, $p < 0.001$ in the mean report mark. When a posthoc pairwise comparison procedure was performed, the

https://doi.org/10.1021/acs.jchemed.2c00387
J. Chem. Educ. 2023, 100, 118−124

Dunnett's T3-values indicated statistically significant differences of the 2019 and 2020 years with both 2016 and 2017, as shown in Table 2. In contrast, the 2021 results only differed statistically significantly from the 2016 ones. Identical results were obtained with the Games-Howell and Tamhane's T2 pairwise comparison procedures recommended by Sauder and DeMars.[17] An estimate of the effect sizes was obtained by comparing the 2017 result with the 2020 one. This resulted in a Cohen's d value of 0.38 corresponding to a small to medium -sized effect according to the interpretation guidelines by Sawilowsky.[23]

Table 2. Pairwise Mean Comparison with Dunnett's T3 *p*-Values for the Laboratory Report Mean Marks between the Years[a]

	2016	2017	2018	2019	2020	2021
2016		**0.046**	**0.007**	**<0.001**	**<0.001**	**<0.001**
2017			1.000	**0.039**	**0.026**	0.813
2018				0.234	0.184	0.994
2019					1.000	0.988
2020						0.983

[a]Values significant at the 0.05 or lower level are in bold.

Changes in Student Experiences

Student mean responses to the Likert question "The way that the laboratory work was organized supported my learning" differed significantly according to ANOVA: $F(2,335) = 19.67$, $p < 0.001$. Furthermore, according to the Dunnett's T3 p-values reported in Table 3, the continuous increases in the mean value from 2019 onward were statistically significant at the 0.05 -level between all three years. Again, both the Games-Howell and Tamhane's T2 pairwise comparison procedure yielded identical results. The total increase in the mean corresponds to a large[23] Cohen's d effect size of 0.89. Due to the use of an ordinal Likert scale, these findings were further verified using the Independent-Samples Kruskal–Wallis nonparametric test, which also indicated a statistically significant difference between the distributions of responses of the three years with $H(2) = 35.150$, $p < 0.001$. Additional pairwise comparisons with Bonferroni corrections showed that all differences were significant at the 0.05 level with $p = 0.037$ (2019–2020), $p = 0.000$ (2019–2021), and $p = 0.001$ (2020–2021).

Table 3. Student Mean Responses to the "The way that the laboratory work was organized supported my learning" Five-Point Likert Question from 2019 to 2021

	N	Mean (sd)	Dunnett's T3 *p*-values	
2019	110	3.28 (1.21)	0.038 (2020)	<0.001 (2021)
2020	122	3.67 (1.15)		<0.001 (2021)
2021	106	4.21 (0.85)		

A histogram of the individual response distributions from 2019 to 2021 is provided in Figure 3. It shows that compared to 2019 and 2020, 2021 saw particularly large increases in the Agree and Strongly agree Likert-categories. In contrast, between 2019 and 2020 the number of respondents in the Strongly agree category increased substantially while the number in the Agree category increased only slightly.

Student Open Responses

In the open responses, the improvements in student experiences were seen as a drop in the number of negative comments relative to the number of comments containing positive or both positive and negative elements as shown in Table 4. Meanwhile, the numbers of comments containing only positive and both positive and negative elements were roughly equal between the two years so that in 2021 purely negative comments made up only 17% of the total number of comments. Although the classifications were verified by an independent expert, these quantitative results should be taken with a grain of salt as many students did not provide open responses.

Typical negative themes in 2020 included the high workload associated with the laboratory report, differences in TA competence, strictness of report assessment combined with unclear instructions, grading principles, and submission timelines. Some also felt that the Preparatory Workshop was confusing, like student 86, who wrote in 2020

> *"The Preparatory Workshop was really annoying and practically useless. The only thing it did was create a really uncertain feeling about what the laboratory was about. Everything depended on the TA who was not very clear..."*

Most of the issues raised in the 2020 feedback resulted in modifications in teaching for 2021. For example, more attention was paid to TA training, communication of timelines, and the availability of instructions. Confusing or contradictory sections of the instructions were also rewritten. Consequently, the negative feedback in 2021 focused much more on the workload of the report and the strictness of the assessment, although some still made calls for a return to the expository cookbook-style laboratory instruction. While many praised the design of the laboratory day, they also found the 8 h day exhausting, even when most groups did not require the full 5 h to finish the laboratory part.

As indicated in Table 4, the prevalent attitude toward the laboratory module was positive in 2021, with 38% of open responses containing purely positive elements and another 39% containing both positive and negative elements. For example, student 94 wrote:

> *"The Preparatory Workshop was really good! For the first time during my studies, I felt like I knew what I was going to do when entering the laboratory."*

Many students in both years further highlighted how the lab work and the report not only supported their understanding of chemical thermodynamics but also taught them important writing skills. Several students praised the report assessment process, which divided the writing into multiple smaller tasks. For example, student 82 in 2020 wrote:

> *"...The report was saved by the fact that the submission was divided into smaller parts. This way you worked on it little by little and not in one big crash. In my opinion it was particularly fair that we had the opportunity to revise the report based on the TAs feedback after the submission. The corrections stuck much better to your mind when you had the opportunity to actually incorporate them..."*

Finally, while the number of responses containing both positive and negative elements remained large in both years, these were often the most analytical and nuanced responses. They also included more self-reflection, as exemplified by the response from student 110 in 2020:

> *"The laboratory work itself was nice and easy. Writing the report was challenging as I didn't always quite understand what was required of it. But sure, since this was the first report that I wrote by myself it is going to be challenging in the beginning. I learned a lot of really important skills!"*

https://doi.org/10.1021/acs.jchemed.2c00387
J. Chem. Educ. 2023, 100, 118−124

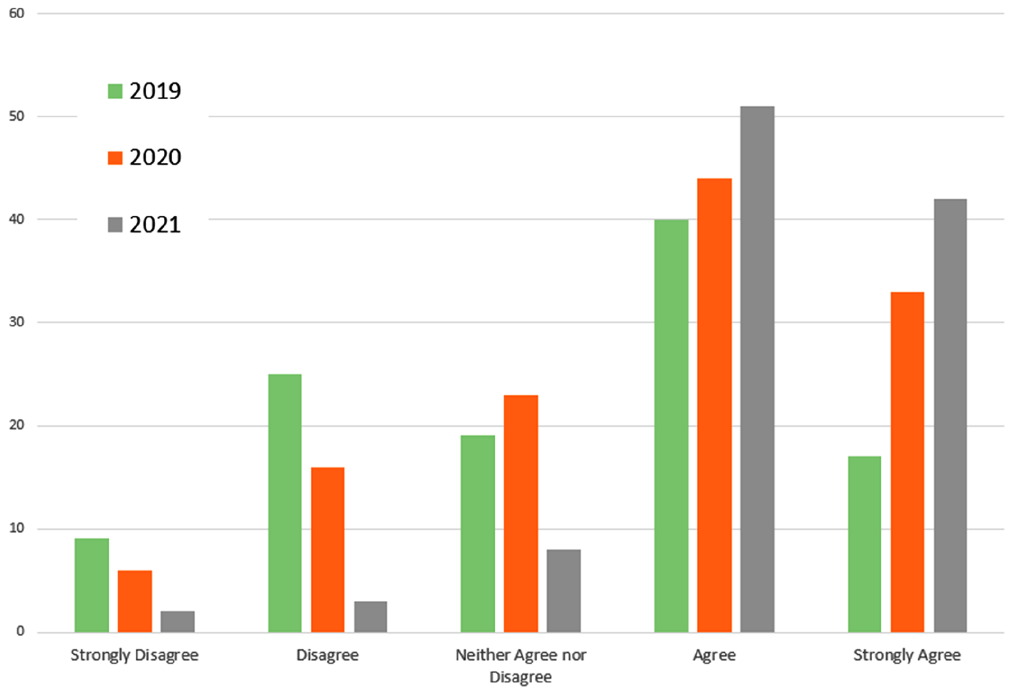


Figure 3. Individual response distributions for the Likert question "The way that the laboratory work was organized supported my learning".

Table 4. Number of Different Types of Open Responses between 2020 and 2021

	2020	2021
Positive	23	24
Negative	28	11
Positive and Negative	27	27
Neutral	0	4

■ DISCUSSION

The primary goal of this action research study was to develop a new guided inquiry thermodynamics laboratory module to improve student learning. The new module showed great promise, resulting in predominantly positive student experiences, in line with previous research.[8,24] The structure also increased the marks students received from the laboratory report when compared with traditional cookbook laboratories. The observed effect sizes were somewhat below the mean effect size of 0.73 observed by Beck et al.[3] in their review for inquiry-based laboratories in biology, and slightly above the POGIL-specific effect size of 0.29 reported by Walker and Warfa.[10]

Interestingly, while there were significant differences between the average laboratory report marks of the pre and postguided inquiry laboratories, the final 2021 results were lower than the 2019 and 2020 results and not statistically significantly different from the preguided inquiry years. At the same time, student opinion was at an all-time high with most students agreeing that the way the laboratory work was organized supported their learning. One related factor is that while the grading matrix remained the same between the years, the penalty for neglecting some of the mandatory corrections listed in the self-assessment rubric was slightly harsher in 2021 compared to 2020. On the other hand, due to the COVID-19 pandemic, the 2021 class had done most of their university studies remotely, which might have negatively impacted their writing and general laboratory skills.

Even though only minor adjustments were made to the laboratory practice between 2020 and 2021, these seem to have had a major impact on students' experiences. The most significant of these was increasing the Preparatory Workshop and laboratory times to 3 and 5 h from 2 and 4, respectively. Indeed, following this adaptation, a much larger proportion of students pointed out the Preparatory Workshop as beneficial to their learning in the open feedback. This underscores the importance of providing students with sufficient time to think and reflect on the learned material. If the teacher wishes to support autonomy there needs to be enough time for students to fail and try again. This increased time requirement is a significant downside of the guided inquiry approach.[11] It can cause logistical challenges especially in larger courses, as the 2021 complaints about the duration of the 8 h laboratory day exemplify.

With respect to student experiences toward the laboratory report, the current study has underlined the strengths of the 360° framework.[15] In particular, the presence of multiple assessment points where different facets of the report were analyzed and the consequent scaffolding of the writing task by breaking it into a series of smaller parts was experienced as beneficial. Similarly, the presence of different types of assessment, including self-assessment and the focus on formative assessment during the writing process, received praise. Interestingly, the original incorporation of peer assessment alongside self-assessment received substantial opposition from the students who felt that it enabled and rewarded plagiarism.

Two themes that significantly negatively impacted student experiences of the laboratory module in 2020 were the lack of TA competence and variability in the strictness of the TA report assessment. Both underline the importance of investing time and effort in a rigorous TA training program that ensures uniform standards of assessment and equips TAs with the skills to succeed. Particularly in cases where TAs are teaching in a format that is unfamiliar to them from their own studies, such as guided inquiry, the training program should provide them with sufficient pedagogical background and hands-on practice.[16]

https://doi.org/10.1021/acs.jchemed.2c00387
J. Chem. Educ. 2023, 100, 118−124

CONCLUSIONS

In this study, I have developed a new guided inquiry thermodynamics laboratory module to improve student learning on two key aspects of chemical thermodynamics, i.e., activity and equilibrium. This module demonstrates how a combination of guided inquiry and a 360° feedback report writing framework can improve both learning outcomes and student experiences. As TAs often play a crucial role in laboratory instruction, their training is of fundamental importance to any pedagogical approach and should include pedagogical, theoretical, and practical instruction to ensure high-quality feedback and guidance. Teachers should also remember to reserve sufficient time for the guided inquiry activities so that students have a chance to think for themselves, engage in creative problem solving, and make mistakes.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.2c00387.

Online Feedback Form, Step-by-Step Laboratory Guide for Instructors, Background Material, Preparatory Workshop Guidance Sheet, Laboratory Report Assessment Rubric, TA Pedagogical Training Material, Laboratory Guidance Sheet, Guidance Sheet Solutions (PDF)

AUTHOR INFORMATION

Corresponding Author

Lauri J. Partanen − *Department of Chemistry and Materials Science, Aalto University, FI-00076 Aalto, Finland;* orcid.org/0000-0002-9962-2015; Email: lauri.partanen@aalto.fi

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.2c00387

Notes

The author declares no competing financial interest.

ACKNOWLEDGMENTS

I would like to thank Liisa Myyry from the University of Helsinki for performing an independent analysis of the course feedback data to enhance the validity of the research findings.

REFERENCES

(1) Domin, D. S. A Review of Laboratory Instruction Styles. *J. Chem. Educ.* **1999**, *76* (4), 543−547.

(2) Concannon, J. P.; Brown, P. L Transforming Osmosis: Labs to Address Standards for Inquiry. *Sci. Act.* **2008**, *45* (3), 23−26.

(3) Beck, C.; Butler, A.; da Silva, K. B. Promoting Inquiry-Based Teaching in Laboratory Courses: Are We Meeting the Grade? *CBE Life Sci. Educ.* **2014**, *13* (3), 444−452.

(4) Zion, M.; Sadeh, I. Curiosity and Open Inquiry Learning. *J. Biol. Educ.* **2007**, *41* (4), 162−169.

(5) Kirschner, P. A.; Sweller, J.; Clark, R. E. Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching. *Educ. Psychol.* **2006**, *41* (2), 75−86.

(6) Brown, P. L.; Abell, S. K.; Demir, A.; Schmidt, F. J. College Science Teachers' Views of Classroom Inquiry. *Sci. Educ.* **2006**, *90* (5), 784−802.

(7) Chatterjee, S.; Williamson, V. M.; McCann, K.; Peck, M. L. Surveying Students' Attitudes and Perceptions toward Guided-Inquiry and Open-Inquiry Laboratories. *J. Chem. Educ.* **2009**, *86* (12), 1427−1432.

(8) Rodriguez, J.-M. G.; Hunter, K. H.; Scharlott, L. J.; Becker, N. M. A Review of Research on Process Oriented Guided Inquiry Learning: Implications for Research and Practice. *J. Chem. Educ.* **2020**, *97* (10), 3506−3520.

(9) Ural, E. The Effect of Guided-Inquiry Laboratory Experiments on Science Education Students' Chemistry Laboratory Attitudes, Anxiety and Achievement. *J. Educ. Train. Stud.* **2016**, *4* (4), 217−227.

(10) Walker, L.; Warfa, A.-R. M. Process Oriented Guided Inquiry Learning (POGIL®) Marginally Effects Student Achievement Measures but Substantially Increases the Odds of Passing a Course. *PLoS One* **2017**, *12* (10), No. e0186203.

(11) Hunnicutt, S. S.; Grushow, A.; Whitnell, R. Guided-Inquiry Experiments for Physical Chemistry: The POGIL-PCL Model. *J. Chem. Educ.* **2015**, *92* (2), 262−268.

(12) Cole, R. S.; Muniz, M.; Harvey, E.; Sweeney, R.; Hunnicutt, S. How Should Apples Be Prepared for a Fruit Salad? A Guided Inquiry Physical Chemistry Experiment. *J. Chem. Educ.* **2020**, *97* (12), 4475−4481.

(13) Phillips, J. A.; Jones, G. H.; Iski, E. V. Using a Guided-Inquiry Approach to Teach Michaelis − Menten Kinetics. *J. Chem. Educ.* **2019**, *96* (9), 1948−1954.

(14) Boyd-Kimball, D.; Miller, K. R. From Cookbook to Research: Redesigning an Advanced Biochemistry Laboratory. *J. Chem. Educ.* **2018**, *95* (1), 62−67.

(15) Tee, D. D.; Ahmed, P. K. 360 Degree Feedback: An Integrative Framework for Learning and Assessment. *Teach. High. Educ.* **2014**, *19* (6), 579−591.

(16) Wheeler, L. B.; Clark, C. P.; Grisham, C. M. Transforming a Traditional Laboratory to an Inquiry-Based Course: Importance of Training TAs when Redesigning a Curriculum. *J. Chem. Educ.* **2017**, *94* (8), 1019−1026.

(17) Sauder, D. C.; DeMars, C. E. An Updated Recommendation for Multiple Comparisons. *Psychol. Sci.* **2019**, *2* (1), 26−44.

(18) Graneheim, U. H.; Lindgren, B.-M.; Lundman, B. Methodological Challenges in Qualitative Content Analysis: A Discussion Paper. *Nurse Educ. Today* **2017**, *56*, 29−34.

(19) Gibbs, P.; Cartney, P.; Wilkinson, K.; Parkinson, J.; Cunningham, S.; James-Reynolds, C.; Zoubir, T.; Brown, V.; Barter, P.; Sumner, P.; MacDonald, A.; Dayananda, A.; Pitt, A. Literature Review on the use of Action Research in Higher Education. *Educ. Action Res.* **2017**, *25* (1), 3−22.

(20) Nolen, A. L.; Putten, J. V. Action Research in Education: Addressing Gaps in Ethical Principles and Practices. *Educ. Res.* **2007**, *36* (7), 401−407.

(21) Agustian, H. Y.; Seery, M. K. Reasserting the Role of Pre-Laboratory Activities in Chemistry Education: A Proposed Framework for their Design. *Chem. Educ. Res. Pract.* **2017**, *18* (4), 518−532.

(22) Ryan, R. M.; Deci, E. L. Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions. *Contemp. Educ. Psychol.* **2000**, *25* (1), 54−67.

(23) Sawilowsky, S. S. New Effective Size Rules of Thumb. *J. Mod. Appl. Stat. Methods* **2009**, *8* (2), 597−599.

(24) Vishnumolakala, V. R.; Southam, D. C.; Treagust, D. F.; Mocerino, M.; Qureshi, S. Students' Attitudes, Self-Efficacy and Experiences in a Modified Process-Oriented Guided Inquiry Learning Undergraduate Chemistry Classroom. *Chem. Educ. Res. Pract.* **2017**, *18* (2), 340−352.