Guided-inquiry laboratory experiments in the analytical chemistry laboratory curriculum

Sayo O. Fakayode

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Introduction

The utility of guided-inquiry laboratory experiments (GILEs), in which students have considerable autonomy in the design and execution of the experiment, continues to be of active pedagogical research interest as a means of stimulating students' achievement and interest in science, technology, engineering, and mathematics (STEM) disciplines [1–31]. Studies have shown that GILEs promote students' learning, improve students' critical thinking, promote teamwork, improve students' leadership skills, and offer distinct advantages over traditional “cookbook” experiments where students simply follow a lab manual. Accordingly, GILEs have been incorporated into analytical chemistry (quantitative and instrumental) laboratory and other laboratory curricula in several institutions and high schools [1–31]. Fascinated by the aforementioned advantages of GILEs in promoting students' learning, I started the incorporation and implementation of GILEs in my analytical chemistry laboratory course early in my professional career as an assistant professor at Winston-Salem State University (WSSU). I developed several GILEs including the determination of heavy metals in toys and children's products, determination of physical and chemical properties of water samples, a coulometric Karl Fischer titration of the moisture content of over-the-counter pharmaceuticals and dried food products, a purity analysis of the pharmaceuticals naproxen and propranolol, and a determination of the iron content of foods [1].

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S. O. Fakayode (✉)
Department of Chemistry, North Carolina A&T State University,
Greensboro, NC 27411, USA
e-mail: sofakayo@ncat.edu

A detailed description of the format of the course in which I use GILEs has been previously published [1]. In brief, seminar presentations and training on laboratory safety, ethics in research, scientific writing, and plagiarism are provided to the students before the commencement of the project. Students work in groups to promote teamwork. Students perform an extensive literature search using SciFinder, Science Direct, American Chemical Society (ACS) journals, and other online resources to obtain background information on the technique(s) and instrumentation they will utilize for their assigned project prior to the beginning of lab work. However, the incorporation and implementation of GILEs may pose a considerable challenge to students and instructors. The focus of this article is to describe the challenges I encountered using GILEs and the strategies I have used for the successful design and implementation of GILEs in my laboratory courses.

Challenges of using GILEs in an analytical chemistry laboratory curriculum

GILEs are new to students

The first challenge I encountered was that many students had never experienced an open-ended experiment before. They were comfortable with conventional “cookbook” experiments where handouts or lab manuals described the exact experimental procedure. The extensive literature search, literature analysis, method development, instrumental analysis, data analysis, report writing, and oral presentation required in a GILE was new to them. I also allow the students to resolve challenges or problems that arise with minimum supervision. Consequently, some students balked at the additional responsibilities required in GILEs. I utilize several strategies to address this challenge. One is to engage in a frank discussion with students about the educational advantages of GILEs.

Another is to invite previous participants in my course to share their experiences with the students. Finally, I provide my students with some published articles that describe the advantages of GILEs over conventional experiments. I find these strategies effective in getting some students excited about and other students more receptive toward the GILE approach.

I experienced some frustration at the early stages of implementation because of some students' attitudes, mindset, and perceptions. The more I use GILEs, the more I am convinced of their advantage in promoting student learning and critical thinking ability. Consequently, I am determined not to give up on the implementation of GILEs in my laboratory courses.

Instructor workload

The use of GILEs can be time consuming in the initial stages of design and implementation. I reviewed articles on GILEs used at other institutions. I attended several workshops to learn techniques necessary for effective design and implementation of GILEs. Finally, I had to design experiments that would excite and motivate my students. Considerable time was spent on the development of grading rubrics for the written report, oral presentation, and survey questions to evaluate the students (some are provided in the accompanying Electronic Supplementary Material Tables S1–S3).

Concern for negative student and colleague evaluations

As a tenure-track assistant professor, I was aware that the decision concerning my tenure and promotion would be made by senior faculty, the chair, and school administrators. A lack of support from these individuals would be problematic. The potential for negative student comments about the experience was a concern. Consequently, I had several meetings with chair and some senior faculty about my intentions and goals before GILE was initiated in my laboratory course curriculum. At these meetings, the compelling advantages of GILE in promoting students' learning and success were fully discussed. These discussions were helpful in motivating and generating the interest and support of my chair and some colleagues for my GILEs. In fact, my chair and some senior faculty were not only interested in GILEs, but were implementing similar experiences in their laboratories. I also worked collaboratively with my chair to organize a 1-day GILEs and process oriented guided inquiry learning (POGIL) professional development workshop on campus in order to further expose STEM faculty members and administrators at WSSU to GILEs and POGIL. Faculty members from other institutions in North Carolina were also invited to participate in this workshop. The experts on GILEs and POGIL were invited to give seminar presentations on strategies for

successful design, incorporation, and implementation of GILEs and POGIL in STEM laboratory courses. The workshop also served as an avenue where the concerns and questions of faculty and administrators on GILE and POGIL were addressed by experts. A certificate of attendance was also presented to the participants. Faculty in the chemistry department were encouraged to attend workshops elsewhere to gain a better insight into the design and implementation of GILEs. Finally, I obtained a letter of recommendation in support of my tenure and promotion application from an independent evaluator who conducted a survey that confirmed the students' positive perception of GILEs and its influence in promoting their learning and success.

Budget limitations and instrumental constraints

Some of my GILEs require more supplies and resources than traditional experiments. I have implemented experiments that required the purchase of several food items, pharmaceutical drug samples, reference materials, standards, and reagents that are not commonly used in conventional experiments. Obtaining resources with a limited budget during severe university budget cuts can be a challenge, particularly in a small department or at a minority institution. To minimize the cost, I developed relatively inexpensive experiments that could be completed within the limit of the available resources. Using the same experiments in subsequent years means that certain chemicals and supplies may already be available. I sought and obtained extramural funding for the development of GILEs through the Title III Program of the US Department of Education and National Science Foundation curriculum development grants.

Incorporating and managing GILEs

When first starting, I was uncertain about how many experiments and lab periods to devote to GILEs. I wanted to include some traditional experiments as a way of training students in certain fundamental skills. Therefore, I had to design a GILE that could be completed in a reasonable amount of time. I started with a relatively simple GILE that could be completed within three lab meeting periods. The experiment was assigned to students at the beginning of the semester so they had time to review literature, design a work plan, and select an analytical method while they conducted other traditional experiments. This strategy allowed my students to cover fundamental principles and instrumental techniques they would likely use while planning for their GILE. While I still continue to have each student conduct one GILE per semester, the scope and complexity of the experiments have increased over the years. My initial GILEs were simple, typically requiring

the use of one or two analytical techniques. The GILEs I use now are more challenging and require the students to utilize multiple analytical methods and instruments. My ultimate goal is to gradually phase out the use of traditional lab experiments and eventually to use only GILEs.

Effective monitoring of many students working simultaneously on different instruments can be challenging, especially when the analytical instruments are not present in the same room. Consequently, I now use GILEs that can be conducted with instruments housed in the same laboratory. This allows different groups to work on their project simultaneously while I can attend to the needs of each group. My department has a lab manager who helps me in training the students outside scheduled laboratory periods on the use of the instrumentation. The scheduled laboratory periods are primarily devoted to activities such as sample and standard preparation and operating the instrumentals.

Teamwork and group dynamics

GILEs are best done in groups to promote teamwork and to improve student leadership skills. My hope is to have groups where everyone works well together and contributes equally to complete the project. However, people working in groups can have problems because of individual personality issues, resentment, and unwarranted destructive competition [32]. I have sometimes encountered negative attitudes toward teamwork in my lab. For example, I have experienced a situation where a student prefers not to work in a group. I have found it important to communicate with the students throughout the semester about the importance of collaboration and teamwork to successfully complete their project. I also discuss the ne-

cessity of teamwork in industrial, academic, or government settings. Fortunately, I have never experienced any major student personality conflicts in my course. However, I am always prepared for that possibility and am ready to intervene should the need arise.

The appropriate group size depends on the class size, the number of available analytical instruments, equipment, and other laboratory resources, as well as the nature and amount of work in the experiment. My analytical chemistry lab is relatively small with a maximum of 20 students. Accordingly, my groups often consist of 2 or 3 students. I assign students to groups. Using their transcripts, I make sure each group has a mix of stronger and weaker students. I often observe that the weaker students are motivated in their efforts by the stronger students. Another challenge with group activities is ensuring that all group members are fully and actively involved in the project. I often assign each member a specific role(s). I may designate a student as a group leader, a group recorder, or a group reporter. The role of the group leader is to oversee the overall activity, progress, or challenges the group may encounter. The group recorder is responsible for maintaining accurate record keeping of sample collection, sample preparation, instrumental analysis, and data analysis. The group reporter is responsible for the communication of the group activity, results, and findings to each member of the group and to me for review. The actual lab work is typically completed in three lab periods. However, the GILEs are multi-phased projects involving a literature search, literature review, sample collection, understanding the instrument required for the analysis, actual lab work, data analysis and data interpretation, report writing, and oral presentations. These activities require that students work throughout the semester on their project.

Table 1 Summary of student responses to the GILE experience in the spring of 2013

Survey question	Strongly agree and agree %	Neutral %	Strongly disagree and disagree %
1. Did you find your GILE interesting and exciting?	92.3	7.7	0
2. I was mentally challenged by my GILE project	84.6	15.4	0
3. This GILE project enhances my critical thinking ability for problem solving and to work independently	92.3	7.7	0
4. GILE improves my written and verbal communication skills	84.6	15.4	0
5. GILE motivates me in research and other scholarly activity	92.3	7.7	0
6. GILE strengthened my teamwork spirit	100	0	0
7. I prefer the GILE to the traditional lab where I simply follow direction and lab manual	69.2	15.4	15.4
8. I prefer the traditional lab where I simply follow direction and lab manual to GILE	30.8	15.4	53.8
9. I would love to participate in future GILE in other laboratory courses	92.3	7.7	0
10. Overall, I found this GILE useful and beneficial to my future professional development	100	0	0

N=13

Consequently, I often rotate the responsibilities of each group member during the semester at different phases of the project. I frequently award a group grade to promote full participation while also recognizing individual efforts in a team.

Use of technology

The students' first responsibility in a GILE is to obtain information and literature related to their assigned project. I encourage the students' use of laptops, portable electronic devices, and smart phones in my lab. The computers in the lab are networked with internet access, facilitating instant access to online educational resources, including ACS journals, Science Direct, SciFinder, the Sigma-Aldrich website, etc. The use of these devices and resources in the lab allows for rapid communication between group members and me as they design and implement their project. Students are closely monitored to ensure that the technology is only used for educational purposes related to the experiment and does not violate laboratory safety regulations. Any student who is distracted or in violation of the laboratory safety rule automatically loses the privilege of the use of that technology in the laboratory.

Evaluation of the student experience

Various strategies including student rating of laboratory instruction and course evaluation, pre and post personal discussion with students, and student surveys have been used to assess the students' experience. I have also invited an independent evaluator on several occasions to my teaching lab to have confidential discussions and administer surveys to the students. When I first initiated the implementation of GILEs as a new tenure-track assistant professor, I was concerned about negative and/or poor student evaluations. For example, in addition to some favorable comments, I received students' comments such as *"the work in this GI lab is way too much"*, *"I don't understand why I need to do this laborious lab"*, *"I hate this GI lab"*, *"this is a lot"*, *"I spent so much time on this lab that I could have used to study for other classes"*, in the first semester that I used a GILE.

These comments made clear the importance of discussing with students the justification for using a GILE approach, and how the additional time and responsibility in completing these experiments were providing them with skills that would be beneficial in their future career. By discussing this upfront with students, I have found that they are more comfortable with the GILE format and find it highly beneficial. In fact, now an overwhelming number of students enjoy and value the use of GILEs as demonstrated by positive and favorable students' comments in the last 4 years. Table 1 provides a

summary of student responses in Spring 2013 to a survey of a GILE that involves quality control and analysis of pharmaceuticals. Participation in this survey was voluntary and anonymous. All of the participants (100 %) found the experience beneficial to their future professional development. The majority of the participants (69.2 %) preferred the GILE format to a traditional lab format where they follow lab manual procedures. Also, 92.3 % of the participants expressed an interest in participating in future GILEs in other laboratory courses. Furthermore, most participants found the GILE very interesting, felt it promoted their critical thinking and problem solving ability, and found that it enhanced the spirit of teamwork. Many students now wish that all the labs had been conducted in a GILE format.

Overall, GILEs continue to be critical in providing the opportunity for students to better understand the fundamental and practical utility of analytical techniques they have learned in the courses to solve real-world problems. It is also obvious to me that GILEs are crucial to provide the opportunity for students to experience common challenges often encountered in the laboratory during chemical analysis and to determine strategies for resolving those challenges, thereby promoting students' learning, critical thinking, and problem solving in analytical chemistry courses.

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Sayo O. Fakayode is currently an Associate Professor at North Carolina A&T State University (NCAT) in Greensboro. Prior to his current position he was an Assistant Professor at Winston Salem State University (WSSU). He obtained his Ph.D. in analytical chemistry from Baylor University under the supervision of Marianna A. Busch and Kenneth W. Busch. He was a postdoctoral researcher in Isiah Warner's research group at Louisiana State University. He regularly teaches

courses and labs in quantitative and instrumental analysis, general chemistry for health sciences majors, and physical science. He initiated the use of a GILE at WSSU and continues their use at NCAT. His research interests include chiral drug analysis, guest-host inclusion complexation, analytical spectroscopy, environmental remediation, fluorescence detection of molecules of pharmaceutical, clinical, biomedical, forensic, and environmental interest as well as chemometrics and multivariate analysis, and experimental design for instrumental calibration, process optimization, and process control.