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IMPACT OF THE PEDAGOGY OF SUCCESSIVE QUESTIONING ON CHEMISTRY LEARNING

Abstract: The pedagogy of successive questions (PSQ) is a teaching strategy designed to improve student engagement in chemistry courses. It operates through three stages: interrogation, evaluation, and junction. This study explores the effectiveness of the PSQ strategy by applying it to undergraduate General Chemistry students enrolled in biomedical and pharmacy programs at the Lebanese International University (LIU). The study involved two sections of the General Chemistry course. One section utilised the PSQ method, while the other served as a control group with traditional teaching methods. A survey was conducted to assess student engagement levels. Moreover, the students' academic achievement was compared by analysing the average grades from both sections. Statistical analysis was performed to determine the significance of differences in engagement levels and academic performance. The results showed significant improvements in engagement levels and learning outcomes in the section that followed the PSQ methodology. Those students scored an average of 11 % higher than those in the control group. The PSQ strategy was also found to be comparable to other active learning techniques, such as the flipped classroom model, in terms of enhancing engagement and academic performance. The PSQ strategy is an effective teaching method for enhancing student engagement and improving academic performance in chemistry courses, particularly for students in biomedical and pharmacy programs. The findings suggest that PSQ promotes more interactive and engaging learning experiences, which can lead to better retention of information.

Keywords: pedagogy, engagement, student interactions, successive questions, active learning, chemistry education

Introduction

Pedagogy, by definition, is the art and science of teaching, using wide concepts like gamification and active involvement to further the learning process [1]. Pedagogical approaches are continually evolving to adapt to the needs of learners reflecting shifts in theory, evidence, and context [2-4].

Traditional teaching methods, whereby students may be passively listening to a lecture or even reading materials without engaging with the content, usually result in infrequent interactions within the classroom [5, 6]. There are numerous factors that could contribute to the infrequency of student interactions in the classroom. One of the most prevalent factors is the teaching style. When the teacher predominantly employs lecturing or delivering

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information without actively involving students in discussions or activities, it can restrict opportunities for student interaction [7, 8].

The educational approaches therefore are changing; student-centered learning, active participation, and collaborative activities have become more emphasised [9-13]. These techniques allow for better teaching by engaging the students in activities that require the critical thinking, analysis of information, solving problems, and application of knowledge in useful ways [8, 14, 15]. Furthermore, they encourage the learners to engage with the learning material, their peers, and the instructor [16-18].

Freeman et al. found that active learning environments in science courses increased student performance compared to those in lecture-based courses [19]. Students enrolled in traditional course environments were 1.5 times more likely to fail than students in active-learning classes. Subsequent individual-participant meta-analysis shows that active learning also narrows achievement gaps and reduces failure rates across STEM courses [20]. In health-professions education, recent scoping reviews report that active-learning classrooms enhance interactions and participation [21]. Within chemistry, large-scale course analyses report sustained performance gains in active-learning studio formats [22]. As a result, many educators are striving to create environments that encourage more frequent and significant student interactions.

A meaningful learner is one who adeptly builds their own understanding in their mind [23]. Engaged learning enables this construction by involving students in advanced thinking skills and engaging activities [24-27]. Nonetheless, inaccuracies labelled as misconceptions in scholarly works can hinder this learning journey. Courses in biomedical sciences and pharmacy are often seen as complex and abstract, leading to misunderstandings and difficulties in student comprehension, particularly in subjects like chemistry [28-30]. Thus, there is a demand for active learning strategies that foster the construction of knowledge especially in chemistry courses. This demand aligns with constructivist theory, which holds that build (construct) knowledge, rather than just receiving it. New ideas stick only when students connect them to what they already know.

One way of increasing instructor-student interaction is through asking questions. To ask a question opens up the opportunity to obtain important information that might have been precluded [7]. Researchers believe that question-asking (and answering) are very central components in theories of learning, cognition, and education [31-33]. Moreover, there is empirical evidence that improvements in the comprehension, and learning of material can be achieved by training students to ask questions. Effective questioning is an art that empowers both educators and learners to unlock the hidden riches of knowledge.

Socratic seminar is a popular method of promoting student engagement and building more understanding through student-led, evidence-based discussion. In a Socratic seminar, students question and respond to open-ended questions about a certain topic. The method assists in developing disciplined questioning, metacognitive awareness, shared sense-making [34].

Therefore, in order to involve students in the learning process, and enhance their participation in class, the Pedagogy of Successive Questions (PSQ) is applied for undergraduate general chemistry courses. The PSQ is a modified Socratic-seminar approach, adapted to a typical undergraduate general chemistry course at the Lebanese International University. It is a general strategy to enhance student engagement and improve students' grasp of science.

In this paper, we will present the PSQ technique, outlining its key components and implementation process. Subsequently, we will rigorously assess its effectiveness through empirical testing and analysis, providing evidence-based insights into its efficacy and potential impact.

Materials and methods

The stages of PSQ methodology

The PSQ method is an innovative teaching approach designed to enhance student engagement. This strategy unfolds in three connected and sequential stages. A brief schematic of the stages is shown in Figure 1.

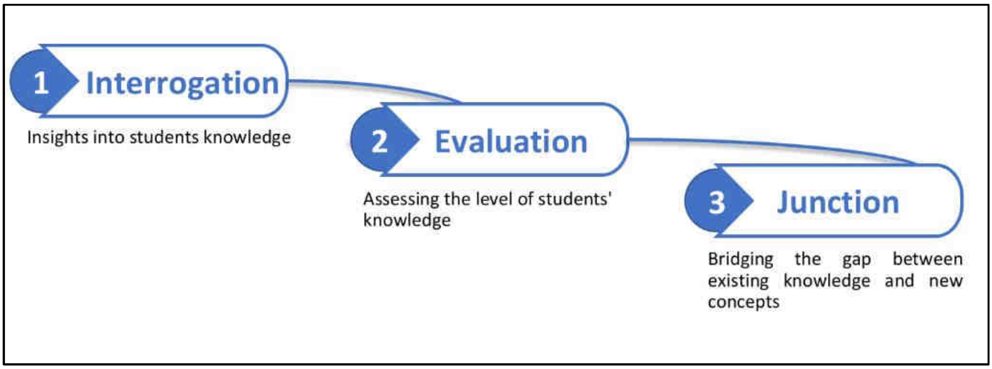

Fig. 1. Schematic representation of the three stages of the PSQ methodology

The PSQ method was applied at the Lebanese International University during fall 2023-2024 semester. The following subsections will provide a practical demonstration of the process in which the chapter of quantum mechanical model was explained using the PSQ approach. This chapter was chosen since it is a crucial topic in the general chemistry curriculum. For the sake of space, we chose to focus on illustrating only one chapter. However, it is important to note that this strategy was applied throughout the entire general chemistry course. By narrowing our demonstration to a single chapter, we can offer a detailed and clear example of how the approach works in practice.

Stage 1: Interrogation phase, Insights into students' knowledge

The first stage of the PSQ method is the interrogation phase where the instructor introduces the topic by asking a series of questions. Breaking the ice with familiar questions can be a great way to engage students and spark their interest in the subject.

The types of questions that should be asked must be fundamental and straightforward in order to decrease the tension and anxiety of the learners. Hence, they are motivated to respond as most of them know the answers, thus, increasing instructor-student interaction.

Stage 2: Evaluation phase, assessing the level of students' knowledge

The second stage of the PSQ method involves assessing students' levels. This critical educational step helps instructors gauge students' knowledge and skills. Understanding where students stand, in terms of knowledge, allows educators to tailor their instruction to meet the specific needs of all learners.

At this stage, the instructor conducts a diagnostic assessment, which serves as a form of evaluation. This analysis is meant to give an overall perspective of students' background knowledge. The instructor reads through the students answers and tries to identify patterns or misunderstandings. Such detailed tracking is important since it can help identifying specific points of difficulty for students or concepts that require additional review.

Stage 3: Junction: bridging the gap between existing knowledge and new concepts

Following the assessment, it is the turn of the educator to summarise all the data that have been collected and to prepare the learners to receive the new information to be seized, initiating the final stage of the PSQ strategy. A junction is made between the concept reached and the new information to be revealed, connecting the ideas with each other.

It is of high importance at this stage to encourage the students to ask questions. Asking questions grant an open discussion between the learners and educators that allows them to seek clarification and deepen their understanding of the subject matter. It helps them to connect new information to their prior knowledge. When students ask questions, they learn to analyse and evaluate information, which are crucial skills for academic and real-life situations.

After answering students' questions and clearing up any confusion, the instructor then proceeds to explain the various aspects of the chapter. It is important to ensure that any information provided connects to what the students already know. This can create a smoother transition and deeper understanding of the subject matter.

Employment of the PSQ method

Interrogation phase

The quantum mechanical model illustrates the atomic structure and subatomic systems incorporating principles such as wave-particle, uncertainty and the probabilistic nature of electron positions. Instead of introducing the concept of quantum model by delivering the ideas directly to the students, similar to the traditional teaching techniques, the first stage of the PSQ strategy is to initiate the topic by asking a set of questions.

The questions to be asked are familiar to the students and serve as a pre-stage for the topic, helping them to activate their prior knowledge and set the foundation for deeper exploration.

At this level of education (undergraduate), the students already have some insights about the structure of the atom and its sub-particles. Hence, the instructor aimed his queries towards these notions. The questions asked by the instructor are presented in Figure 2 such as: "what is an atom; what is the structure of the atom; what is an electronic configuration" these types of queries are simple and straightforward, which allow the students to give a clear reply displaying their knowledge and scientific backgrounds.

Questions are strategically drafted to take students along a step-by-step journey through identifying how atoms are made. They begin with the basic question as to how atoms are formed, identifying the constituent particles and determining their locations within the atomic structure. Each question is related to the other in such a way that students can build up a proper understanding of atomic behaviour. Gradually, more and more complex questions are posed to the audience until they failed to give a clear response.

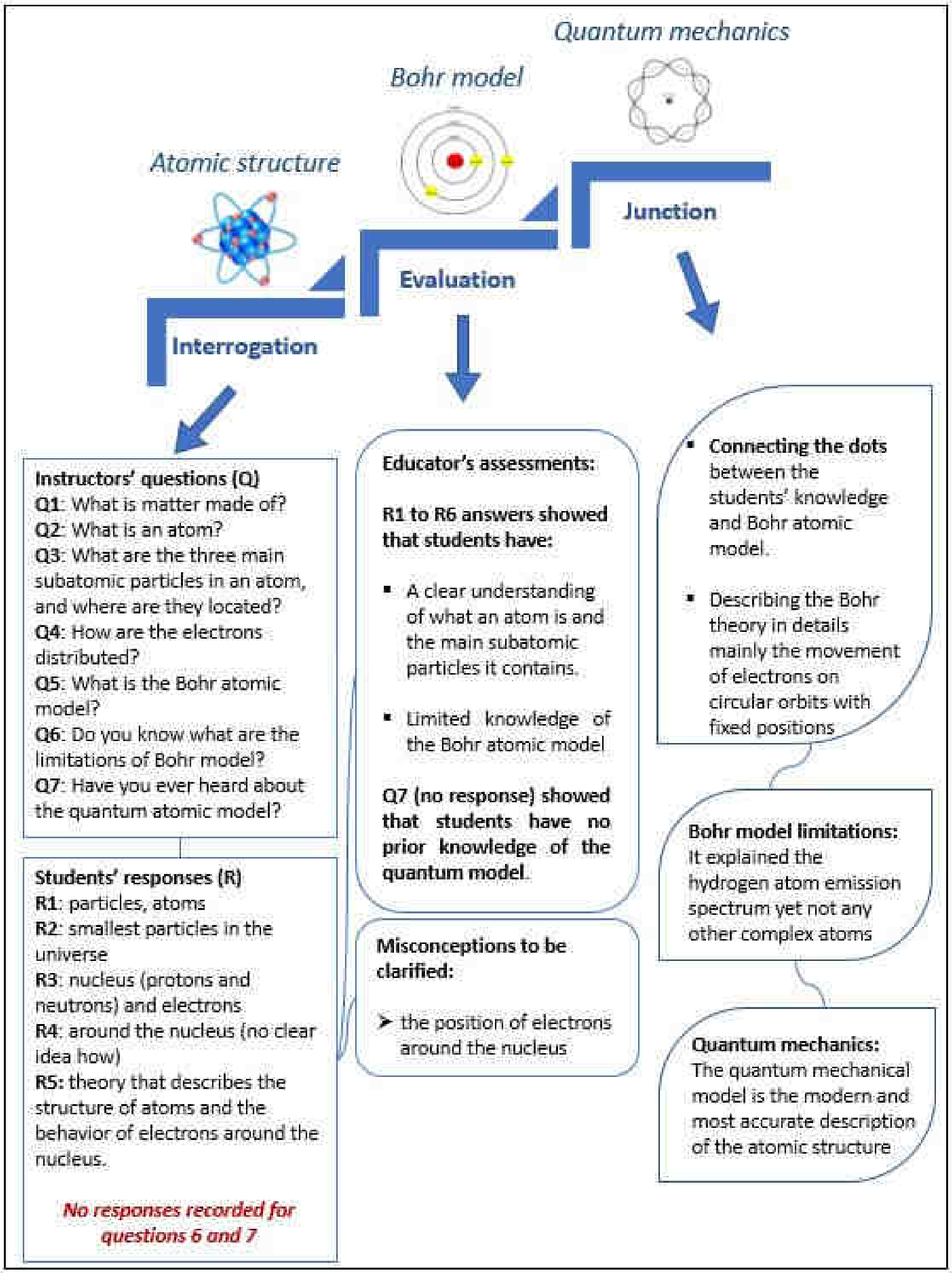

Fig. 2. Schematic representation of the PSQ method applied to the quantum model chapter, detailing the three stages

Approximately 60 % of the students participated in answering the initial set of questions, demonstrating that the majority had a solid foundation in their prerequisite knowledge. This response rate indicates that the students are engaged with the material at the start of the lesson. For the remaining 40 % of the students, the instructor reached out to them during class time and found that most of them were already familiar with the material discussed so far. Through these student-instructor discussions, it became clearer that their hesitation to answer was not due to a lack of understanding but rather a need for more confidence in engaging with the content. At this point, almost all the students were actively engaged with the instructor and were able to grasp the fundamental concepts before moving forward.

Evaluation phase

The answers of the students are collected and also shown in Figure 2. The instructor evaluates the replies to gain an understanding of student's background knowledge. From responses 1 through 5 (R1 to R5), it was inferred that almost all the students have an explicit knowledge about the structure of the atom. From response 4 (R4), it was interpreted that the students have some misconceptions related to the location of the electrons around the nucleus. However, after asking questions 6 and 7, there was a noticeable lack of engagement, as no students responded. This silence indicates the absence of knowledge about the quantum mechanical model. In short, it was evaluated by the instructor that the background knowledge of the students ends at the limitations of the Bohr atomic model.

Junction phase

After evaluating the responses, the junction phase was planned. The plan was to start by reviewing the Bohr atomic model and highlighting its key achievements. This phase would emphasise the success of the model in explaining the structure of the hydrogen atom and its spectral lines, particularly through the concept of electrons moving in fixed orbits with quantised energy levels [35]. The connection phase then focused on discussing the limitations of the Bohr model, especially its failure to accurately describe more complex atoms and account for the finer details of atomic behaviour. From this point, the plan smoothly transitioned to the quantum model, helping students grasp its core principles, such as electron probability clouds, wave-particle duality, and the uncertainty principle [36, 37].

Participants

The PSQ method was applied at one section of the General Chemistry course for students in biomedical and pharmacy programs to evaluate its effectiveness in enhancing student engagement and academic performance. To compare the results, an additional section served as a control group, where traditional teaching method was used. This comparative approach allowed a clear analysis of the new teaching method's impact on student engagement, providing valuable insights into its efficacy.

Participants in the section using the PSQ method were designated as the group under study (GUS), and those from the section employing the traditional teaching approach were classified as the control group (CG).

To ensure consistency and fairness in the comparison between the students of the GUS and the CG, they were taught using the same syllabus, course content, and as-assessment materials. Moreover, the instructional time allocated, and the learning objectives were identical across both sections. This uniformity ensured that any observed differences in student engagement or academic performance could be attributed primarily to the teaching method employed, rather than variations in curriculum or content exposure.

Survey tool

In order to assess the level of engagement in the different studied sections, a questionnaire was designed and approved by the Lebanese International University Institutional Review Board (IRB Ref: LIUIRB-250516-MNZ-409). The questionnaire was made using Google forms (https://docs.google.com/forms) from scratch and not based on any previous study. The English version of the questionnaire is available as Supplementary File 1. Therefore, a pretesting phase was required. It was tested with a sample of first-year undergraduate general chemistry students. Cronbach's Alpha was used to determine the internal consistency of the questionnaire where a value of 0.826 was obtained, indicating an acceptable level of internal consistency. The English version of the questionnaire is provided as Supplementary File 1. Following pretesting, the survey was sent by email to students in section where the PSQ method was applied, as well as to students in section using the traditional teaching approach. Of the 60 students invited to participate in the survey, 55 responded. Of these, 30 participants are from the GUS where the PSQ method was employed, and the other 25 are from the CG.

Ethics approval and consent to participate

This study received ethical approval from the Institutional Review Board (IRB) at the Lebanese International University (Ref: LIUIRB-250516-MNZ-409, dated 20 Nov 2023). Participants in the research study were informed and gave their consent, with a commitment to ensuring the confidentiality and privacy of their information. The study was conducted in accordance with national regulations, including Decree 5294 (April 19, 2001), and adhered to the ethical standards outlined in the Declaration of Helsinki [38].

Statistical analysis

Data were analysed by using SPSS version 24.0. Descriptive statistics were reported as mean and standard deviation, while frequencies and percentages were reported for all categorical characteristics. Normality was assessed using the Shapiro–Wilk test and visual inspection of histograms, which indicated deviations from a normal distribution; therefore, the Mann-Whitney U test was employed to compare the group under study (GUS) with the control group (CG). This non-parametric test is ideal for analysing the contrasts between two independent groups, especially when the data may not follow a normal distribution. It was used to examine the differences in the parameters of the effectiveness of the PSQ method. The test was conducted with a 95 % confidence level, meaning the degree of significance was set at 5 %. If the p-value obtained from the test is less than 0.05, it indicates that the difference between the two groups is statistically significant. However, if the p-value is greater than 0.05, it suggests that there is no substantial variation between the two groups.

Results

Survey results

Figure 3 presents the results of the Likert scale survey conducted to assess student engagement across the two different studied groups. Each statement in the survey was rated by respondents on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree), reflecting their level of agreement with the various statements about their classroom experience. Figure 3 organises the responses in percentages to highlight key trends and variations in engagement, offering a clear visual representation of how students felt about participation, and interaction during lessons.

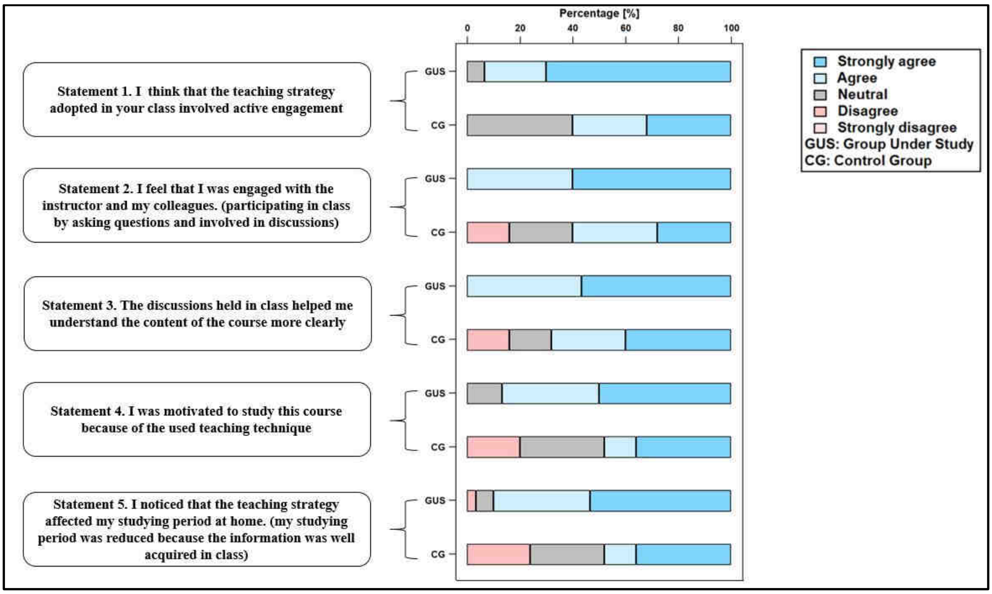

Fig. 3. The statements used in the Likert scale survey were conducted to assess student engagement across the two different studied groups. Each statement in the survey was rated by the respondents

The results of Likert scale survey provide a compelling comparison between the two teaching methods, clearly showing that the PSQ method fostered significantly higher levels of student engagement than traditional teaching method. For almost all the statements used in the survey, the PSQ method consistently received higher ratings, with the majority (around 90 %) of the responses clustered in the 4 (Agree) and 5 (Strongly Agree) categories. The remaining responses were distributed between fair or disagree. This suggests that the interactive nature of the PSQ method successfully captured students' attention and kept them engaged throughout the learning process.

In contrast, the control group section which followed a more traditional lecture-based approach, showed a more varied distribution of responses. A significant number of students (around 40 % to 60 %) rated their engagement at 2 (Disagree) or 3 (Neutral), especially for statements like "I feel that I was engaged with the instructor and my colleagues". This suggests that while the traditional method may have delivered the content, it did not inspire the same level of active participation or enthusiasm among students. Many likely felt more passive in their learning experience, which led to a lower engagement overall.

The contradiction in responses between the two methods highlights the importance of the PSQ method, which is mainly a student-centered teaching strategy. The PSQ method created a more dynamic and engaged classroom environment, compared to the other section where the traditional teaching approach may have contributed to a less engaging atmosphere.

Table 1 presents the results of the Mann-Whitney U test used to compare the responses of students exposed to the PSQ method (GUS) with those taught using conventional methods (CG). This analysis was conducted to evaluate whether there were statistically significant differences in engagement and perception between the two groups. The table includes the U values and corresponding *p*-values for each survey statement. A *p*-value less than 0.05 indicates a significant difference, suggesting that the observed variation is unlikely to have occurred by chance.

Table 1

Survey statement Likert scale scores from strongly disagree (1) to strongly agree (5) in both studied groups. Mann-Whitney U test degree of significance; *N*: size of the population studied; *SD*: standard deviation; *p*-value: degree of significance; GUS: group under study; CG: control group; * Significant finding

Survey statements used to evaluate engagement level	**Group**	**Population size (*N*)**	**Mean**	**Standard deviation (*SD*)**	***p*-value**
Statement 1: I think that the teaching strategy adopted in my class involved active engagement	GUS	30	4.64	0.86	0.0015*
	CG	25	3.92	0.62	
Statement 2: I feel that I was engaged with the instructor and my colleagues? (participating in class by asking questions and involved in discussions)	GUS	30	4.60	1.06	0.0010*
	CG	25	3.72	0.49	
Statement 3: The discussions held in class helped me understand the content of the course more clearly	GUS	30	4.57	1.11	0.0339*
	CG	25	3.92	0.50	
Statement 4: I was motivated to study this course because of the used teaching technique	GUS	30	4.37	1.19	0.0217*
	CG	25	3.64	0.72	
Statement 5: I noticed that the teaching strategy affected my studying period at home? (my studying period was reduced because the information was well acquired in class)	GUS	30	4.40	1.23	0.0155*
	CG	25	3.60	0.78	

Students background academic record

To compare the academic backgrounds of the students, their Grade Point Averages (GPAs) were analysed. A GPA is a standardised numerical measure that reflects a student's average academic performance over a specified period. Typically calculated on a scale from 0 to 4.0, this metric provides a consistent basis for evaluating prior academic achievement across diverse educational settings.

An independent samples t-test was conducted to compare the GPA of students in the control group (CG) and the group under study (GUS). Results showed a statistically significant difference in GPA between the two groups ($t = -2.191$, $p = 0.031$). The negative *t*-value indicates that students in the GUS had a significantly lower average GPA than those in the CG group. A lower GPA generally reflects weaker academic performance, suggesting that students in the GUS have entered the course with a lower academic baseline.

Students' academic achievements

Student academic achievements were assessed by analysing the overall grades of the students. This included midterm exam, quizzes, and the final exam. These aggregated scores served as indicators of the overall academic performance and comprehension achieved by the students throughout the course. The overall grades for both groups are shown in Figure 4.

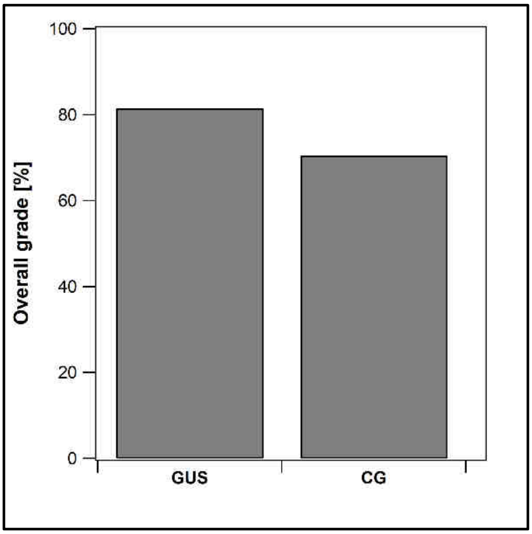

Fig. 4. Comparison between overall grades obtained in the group under study (GUS) and the control group (CG)

Discussions

Impact of the PSQ method on students' engagement levels

To determine whether the students exposed to the PSQ method showed a statistically significant difference compared to those taught using conventional methods, the Mann-Whitney U test was employed to compare the group under study (GUS) with the control group (CG). The results of the Mann-Whitney U test are shown in Table 1. For each survey statement, the *p*-value indicated a statistically significant difference between the two groups. All *p*-values were below 0.05 (see Table 1), this pattern of results shows that students taught using the PSQ method experienced a significantly different engagement environment than those taught using traditional methods. This suggests that the observed improvements in GUS are unlikely to be due to random variation and can be attributed to the effectiveness of the PSQ teaching approach.

Impact of the PSQ method on students' academic performance

A comparative analysis of student academic backgrounds and course performance provides evidence supporting the effectiveness of the PSQ teaching strategy. An independent samples *t*-test revealed a statistically significant difference in GPA between the group under study (GUS) and the control group (CG). This finding indicates that students in the GUS entered the course with a lower academic baseline. Despite this difference, the PSQ method was associated with a notable improvement in student academic outcomes. As shown in Figure 4, students in the GUS taught using the PSQ strategy achieved an average grade of 81.5 %, compared to 70.5 % for those in the CG, an 11 % difference. While this improvement may appear modest, it reflects enhanced learning and comprehension facilitated by the PSQ method. Additionally, the PSQ approach led to a 17.6 % difference in engagement between students and instructors, supporting its interactive and student-centred nature. Together, these results suggest that the PSQ strategy not only fosters greater academic performance but also creates a more engaging learning environment, making it a promising model for active learning in biomedical and pharmacy education.

Comparing the PSQ strategy to other active learning techniques

To enhance student performance and engagement in the classroom, a variety of modern and innovative active learning strategies are increasingly incorporated [39-41]. These include the flipped classroom model [42, 43], case studies, group work, and other interactive methods [44-46]. Such approaches have led to a notable improvement in students' understanding and retention of information, increased engagement and motivation in the classroom, and enhanced communication skills.

One of the most adopted techniques is flipped classrooms since it showed a significant increase in student engagement, retention of information and effectiveness in class time [47-49]. This approach reverses the traditional teaching by having students review pre-recorded lectures at home, dedicating class time to problem-solving and interactive activities. The outcomes of this method showed improvements in test scores ranging from 10 % to 20 % and an increased student-student and student-instructor interaction of 20 % due to the extra time in class [47]. Although this modern strategy showed an increased interest over the years, one of the most challenging aspects, is that it requires extra efforts from instructors in preparing pre-recorded lectures, which are more time consuming compared to traditional teaching strategies [50]. Moreover, both students and educators need access to advanced technologies and applications. A simple comparison between the PSQ approach and flipped classroom model showed similar results in terms of student engagement and grades enhancement. The PSQ method managed to reach a difference in students' test scores by 11 % (10 % to 20 % compared to flipped classroom) and 17.6 % engagement difference (flipped classroom 20 %). These findings indicate that without extra class time and advanced applications and technologies, the PSQ method was able to generate acceptable outcomes compared to that of flipped classrooms, indicating its efficiency as an active learning model.

Study limitations

This study has several limitations that should be acknowledged. First, the research was conducted at a single institution (Lebanese International University) with one cohort of undergraduate students in the biological and chemical departments. This context specificity may limit the generalisability of the findings, as results may not readily extrapolate to other universities, disciplines, or student populations.

Second, the sample size was relatively small, with a total of 55 student participants (30 in the PSQ group and 25 in the control group). This modest number of participants reduces the statistical power of the analyses and may limit the robustness of the conclusions. A larger sample would be needed to increase confidence in the effect sizes observed and to ensure that the results are representative of broader student populations.

Third, the implementation of the PSQ method was described in detail for only a single chapter (the quantum mechanical model) in this report. Although the PSQ pedagogy was applied throughout the entire general chemistry course, focusing the description on one chapter provides only a narrow illustration of the approach. As a result, readers gain insight into the PSQ method's use in that one context, but the paper does not showcase its application across multiple topics. This limitation may restrict understanding of the method's full scope and versatility.

Finally, the survey instrument used to measure student engagement was a novel questionnaire developed specifically for this study, rather than an existing validated instrument. While this custom survey demonstrated acceptable internal consistency (Cronbach's α = 0.826), the lack of prior external validation introduces uncertainty regarding its overall validity and reliability. Therefore, findings related to student engagement should be interpreted with caution given the invalidated nature of the measurement tool.

Conclusion

This study demonstrates that the Pedagogy of Successive Questions (PSQ) is an effective active-learning strategy for General Chemistry students in biomedical and pharmacy programs. Despite beginning the course with a lower average GPA than the control group, students in the PSQ section reported significantly higher engagement on all survey items and achieved an 11 % higher overall course average than peers taught using traditional methods.

The structure of PSQ appears central to these outcomes. The interrogation phase begins with simple, familiar questions that most students can answer, lowering anxiety and normalising participation. The evaluation phase provides the instructor with real-time evidence of students' prior knowledge and misconceptions, enabling targeted clarification of challenging topics such as the quantum mechanical model. Finally, the junction phase explicitly links existing conceptions (e.g. the Bohr model) to more abstract quantum ideas and encourages further student questioning, supporting deeper conceptual understanding.

Together, these three stages create a coherent, question-driven learning trajectory that keeps students engaged, which likely underpins the observed gains in both engagement and academic achievement. The PSQ method thus offers a feasible, low-technology alternative to other active-learning approaches while still producing meaningful improvements in chemistry learning.

Future directions

The pedagogy of successive questions will be implemented across various sections at the Lebanese International University (LIU) on all campuses throughout Lebanon to assess its efficiency on a larger scale. The aim is to evaluate its effectiveness in enhancing student learning outcomes, engagement, and overall teaching quality. This large-scale implementation will permit collecting extensive data and insights, enabling a thorough assessment of the pedagogy's performance across various environments. The future work will aid in refining the pedagogy based on the collected data, addressing any identified limitations.

References

[1] Mortimore P. Understanding Pedagogy: And Its Impact on Learning. London: Sage; 1999. Available from: http://digital.casalini.it/9781849206693.

[2] Subramaniam B, Middlecamp CH. What is feminist pedagogy? Useful ideas for teaching chemistry. J Chem Educ. 1999;76(4):520. DOI: 10.1021/ed076p520.

[3] Christiansen MA. Inverted teaching: Applying a new pedagogy to a university organic chemistry class. J Chem Educ. 2014;91(11):1845-50. DOI: 10.1021/ed400530z.

[4] Collins S, Steele T, Nelson M. Storytelling as pedagogy: The power of chemistry stories as a tool for classroom engagement. J Chem Educ. 2023;100(7):2664-72. DOI: 10.1021/acs.jchemed.3c00008.

[5] Buseri JC. The influence of culture on pupils' questioning habits in Nigerian secondary schools. Int J Sci Educ. 1987;9:579-84. DOI: 10.1080/0950069870090507.

[6] Good TL, Slavings RL, Harel KH, Emerson H. Student passivity: A study of question asking in K-12 classrooms. Sociol Educ. 1987:181-99. DOI: 10.2307/2112275.

[7] Michel N, Cater III JJ, Varela O. Active versus passive teaching styles: An empirical study of student learning outcomes. Human Resource Development Quarterly. 2009;20(4):397-418. DOI: 10.1002/hrdq.20025.

[8] Haidet P, Morgan RO, O'malley K, Moran BJ, Richards BF. A controlled trial of active versus passive learning strategies in a large group setting. Adv Health Sci Educ. 2004;9:15-27. DOI: 10.1023/B:AHSE.0000012213.620.

[9] Misra I, Girshick R, Fergus R, Hebert M, Gupta A, Van Der Maaten L, editors. Learning by asking questions. Proc IEEE Conf Computer Vision Pattern Recognition. 2018. DOI: 10.1109/CVPR.2018.00009.

[10] Al-Samarraie H, Shamsuddin A, Alzahrani AI. A flipped classroom model in higher education: a review of the evidence across disciplines. Educat Technol Res Development. 2020;68:1017-51. DOI: 10.1007/s11423-019-09718-8.

[11] Serin H. Flipped classrooms in teaching method courses at universities. Int J Academic Res Business Social Sci. 2019;9(1):573-85. DOI: 10.6007/IJARBSS/v9-i1/5459.

[12] Gilboy MB, Heinerichs S, Pazzaglia G. Enhancing student engagement using the flipped classroom. J Nutrition Educ Behavior. 2015;47(1):109-14. DOI: 10.1016/j.jneb.2014.08.008.

[13] Goodwin JR. What's the difference? A comparison of student-centered teaching methods. Educ Sci. 2024;14(7):736. DOI: 10.3390/educsci14070736.

[14] Chi MTH, Wylie R. The ICAP framework: Linking cognitive engagement to active learning outcomes. Educat Psychologist. 2014;49(4):219-43. DOI: 10.1080/00461520.2014.965823.

[15] Prince M. Does active learning work? A review of the research. J Eng Educat. 2004;93(3):223-31. DOI: 10.1002/j.2168-9830.2004.tb00809.x.

[16] Jung I, Choi S, Lim C, Leem J. Effects of different types of interaction on learning achievement, satisfaction and participation in web-based instruction. Innovations EducTeaching Int. 2002;39(2):153-62. DOI: 10.1080/14703290252934603.

[17] Dixson MD. Creating effective student engagement in online courses: What do students find engaging? J Scholarship Teaching Learning. 2012;10(2):1-13. Available from: https://files.eric.ed.gov/fulltext/EJ890707.pdf.

[18] Ömer D. Student engagement in blended learning environments with lecture-based and problem-based instructional approaches. J Educat Technol Soc. 2012;15(3):310-22.

[19] Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, et al. Active learning increases student performance in science, engineering, and mathematics. Proc Nat Acad Sci. 2014;111(23):8410-5. DOI: 10.1073/pnas.1319030111.

[20] Theobald EJ, Hill MJ, Tran E, Agrawal S, Arroyo EN, Behling S, et al. Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math. Proc Nat Acad Sci. 2020;117(12):6476-83. DOI: 10.1073/pnas.1916903117.

[21] Bingen HM, Aamlid HI, Hovland BM, Nes AAG, Larsen MH, Skedsmo K, et al. Use of active learning classrooms in health professional education: A scoping review. Int J Nursing Stud Advances. 2024;6:100167. DOI: 10.1016/j.ijnsa.2023.100167.

[22] Heeren RS, Kinoshita SR, Lu L, Pollet P. Undergraduate introductory organic chemistry: performance trends and impact of active learning studios. J Chem Educ. 2025. DOI: 10.1021/acs.jchemed.4c01413.

[23] Bodner GM. Constructivism: A theory of knowledge. J Chem Educ. 1986;63(10):873. DOI: 10.1021/ed063p873.

[24] Sisovic D, Bojovic S. Approaching the concepts of acids and bases by cooperative learning. Chem Educ Res Practice. 2000;1(2):263-75. DOI: 10.1039/A9RP90027F.

[25] Hinde RJ, Kovac J. Student active learning methods in physical chemistry. J Chem Educ. 2001;78(1):93. DOI: 10.1021/ed078p93.

[26] Savec VF, Devetak I. Evaluating the effectiveness of students' active learning in chemistry. Procedia-Social Behav Sci. 2013;106:1113-21. DOI: 10.1016/j.sbspro.2013.12.125.

[27] Andrews DA, Sekyere EO, Bugarcic A. Collaborative active learning activities promote deep learning in a chemistry-biochemistry course. Medical Sci Educator. 2020;30:801-10. DOI: 10.1007/s40670-020-00952-x.

[28] Banerjee AC. Misconceptions of students and teachers in chemical equilibrium. Int J Sci Educ. 1991;13(4):487-94. DOI: 10.1080/0950069910130411.

[29] Cros D, Chastrette M, Fayol M. Conceptions of second year university students of some fundamental notions in chemistry. Int J Sci Educ. 1988;10(3):331-6. DOI: 10.1080/0950069880100308.

[30] Nakhleh MB. Why some students don't learn chemistry: Chemical misconceptions. J Chem Educ. 1992;69(3):191. DOI: 10.1021/ed069p191.

[31] Bransford JD, Arbitman-Smith R, Stein BS, Vye NJ. Improving thinking and learning skills: An analysis of three approaches. Thinking and learning skills: Routledge; 2014. pp. 133-206. ISBN: 9781315060149 .

[32] Graesser AC, Person NK. Question asking during tutoring. Am Educat Res J. 1994;31(1):104-37. DOI: 10.3102/00028312031001104.

[33] Tofade T, Elsner J, Haines ST. Best practice strategies for effective use of questions as a teaching tool. Am J Pharmaceutical Educ. 2013;77(7):155. DOI: 10.5688/ajpe777155.

[34] Robinson L. To what extent do Socratic seminar activities encourage engagement in Classical Civilisation lessons? J Classics Teaching. 2023;24(47):65-71. DOI: 10.1017/S2058631022000459.

[35] Bohr NI. On the constitution of atoms and molecules. London, Edinburgh, Dublin Philosophical Magazine J Sci. 1913;26(151):1-25. DOI: 10.1080/14786441308634955.

[36] Williams JM. The spdf Electron Orbital Model Parsed. viXra. 2013. Available from: https://www.gsjournal.net/Science-Journals/Research%20Papers-Quantum%20Theory%20/%20Particle%20Physics/Download/5031.

[37] Schrödinger E. The present status of quantum mechanics. Die Naturwissenschaften. 1935;23(48):1-26. Available from: https://informationphilosopher.com/solutions/scientists/schrodinger/Present_Status.pdf.

[38] Goodyear MD, Krleza-Jeric K, Lemmens T. The declaration of Helsinki. British Medical J Publishing Group; 2007. pp. 624-5. DOI: 10.1136/bmj.39339.610000.BE.

[39] Walker SE. Active learning strategies to promote critical thinking. J Athletic Training. 2003;38(3):263. Available from: https://pmc.ncbi.nlm.nih.gov/articles/PMC233182/pdf/attr_38_03_0263.pdf.

[40] McConnell DA, Chapman L, Czajka CD, Jones JP, Ryker KD, Wiggen J. Instructional utility and learning efficacy of common active learning strategies. J Geosci Educ. 2017;65(4):604-25. DOI: 10.5408/17-249.1.

[41] Pereira-Santos D, Prudêncio RBC, de Carvalho AC. Empirical investigation of active learning strategies. Neurocomputing. 2019;326:15-27. DOI: 10.1016/j.neucom.2017.05.105.

[42] Zuber WJ. The flipped classroom, a review of the literature. Industrial Commercial Training. 2016;48(2):97-103. DOI: 10.1108/ICT-05-2015-0039.

[43] DeLozier SJ, Rhodes MG. Flipped classrooms: A review of key ideas and recommendations for practice. Educat Psychology Rev. 2017;29(1):141-51. DOI: 10.1007/s10648-015-9356-9.

[44] Buehl D. Classroom Strategies for Interactive Learning. Routledge; 2023. DOI: 10.4324/9781032680842.

[45] Senthamarai S. Interactive teaching strategies. J Appl Adv Res. 2018;3(1):S36-8. DOI: 10.21839/jaar.2018.v3iS1.166.

[46] Davis D, Chen G, Hauff C, Houben G-J. Activating learning at scale: A review of innovations in online learning strategies. Computers Educ. 2018;125:327-44. DOI: 10.1016/j.compedu.2018.05.019.

[47] Akçayır G, Akçayır M. The flipped classroom: A review of its advantages and challenges. Computers Educ. 2018;126:334-45. DOI: 10.1016/j.compedu.2018.07.021.

[48] Somaa F. The flipped classroom approach: A review of cognitive styles and academic performances. Cureus. 2024;16(7):e63729. DOI: 10.7759/cureus.63729.

[49] Hussain MI, Preetha R, Naik MS, Panaskar HC, Das AM. Assessing the effectiveness of flipped classroom strategy on student performance. Europ Chem Bull. 2023;12:2883-96. DOI: 10.1186/s12909-024-06105-7.

[50] Wanner T, Palmer E. Personalising learning: Exploring student and teacher perceptions about flexible learning and assessment in a flipped university course. Computers Educ. 2015;88:354-69. DOI: 10.1016/j.compedu.2015.07.008.