Use of Control Charts and Scientific Critical Thinking in Experimental Laboratory Courses: How They Help Students to Detect and Solve Systematic Errors

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Use of Control Charts and Scientific Critical Thinking in Experimental Laboratory Courses: How They Help Students to Detect and Solve Systematic Errors

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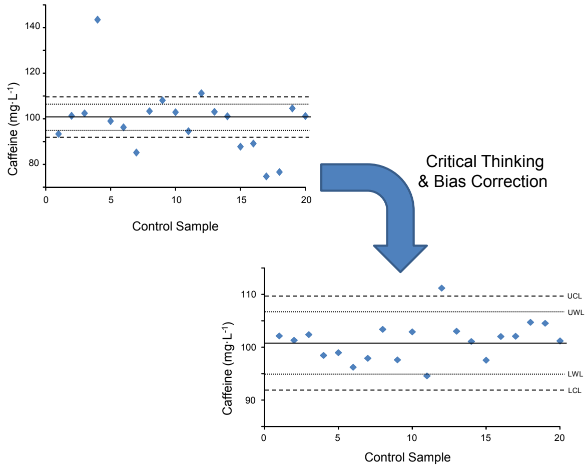
ABSTRACT

Systematic errors are unfortunately common in analyses performed by students in teaching laboratories. Quality control (QC) tools are required to detect and solve bias in laboratory analyses. However, although QC has become routine in real-world laboratories, it is still rarely applied in teaching laboratories. For this reason, systematic errors in students' results remain unknown in many cases. In this study, the use of control charts and critical thinking methodologies are applied in laboratory lessons to show students how the control charts can be used to detect and correct systematic biases in analyses. Students practice how to evaluate out-of-control results by applying scientific critical thinking procedures based on knowledge acquired in previous subjects, aiming to find the source of the bias detected, solve it, and apply rectifying measures to improve the operational procedure. With the proposed methodology, students understand the importance of control charts in demonstrating the quality and validity of the data obtained. During the academic years applying this methodology, the most common source of bias was found to be related to an incorrect application of basic laboratory skills, which shows that these skills need to be learned and, most importantly, put into practice over the whole period of student training and cannot be taken for granted once they have been taught in the early stages of their curricula. The learning outcomes were assessed through an exercise that requires students to evaluate results obtained in the laboratory in previous years. It was found that the majority of students (97.6%) were able to detect a bias, find the source, and solve the error.

GRAPHICAL ABSTRACT



KEYWORDS

Upper-Division Undergraduate, Laboratory Instruction, Hands-On Learning, Student-Centered Learning.

How good are my laboratory results? This is a question that students should ask themselves when performing analyses in the laboratory. Unfortunately, the term “good” cannot be easily defined when dealing with experimental results. It can be said that a test is good or useful if it provides valid information to answer a problem.

Real-world analytical laboratories deal with problems that go well beyond the realm of analyses performed in teaching laboratories,[1] and social, legal, and economical decisions often have to be taken as a result of laboratory measurements. For these reasons, the quality of the results becomes essential. These circumstances are usually not taken into account in teaching lessons, but students should be introduced to this reality as such considerations will become routine once they finish their degrees and start work. To this end, students should deal with aspects such as quality control (QC) and information management in laboratory lessons during their training.

It has also been recommended that students should participate in problem-solving activities by performing analyses that have a purpose and not simply perform experiments focused on showing a theoretical concept explained in a previous lecture.[2] In traditional laboratory courses, students must deliver the result of the analysis of an unknown compound without any decision being required on the basis of this result and with no greater aim or purpose than to confirm a preliminary hypothesis.

These results are usually obtained after measuring replicates of the same sample and conventional statistical methods are applied to calculate the mean value and its variability. For this reason, both the importance of statistics in testing methods and of teaching students how to use them in the laboratory have long been recognized,[3] which is reflected in the presence of specific statistical subjects in many scientific degrees. However, it is not common for students to discuss problems and systematic errors that are encountered during analyses.[4] This requires the development of a process thinking laboratory methodology (using past performance to predict future outcome), which changes the way statistical methods are used for the display and evaluation of data. QC is an essential part of this process thinking methodology that has become a significant issue in industrial and contract laboratory practice. However, in the best of cases, QC is only peripherally discussed in many curricula[5] and students may be left with the idea that it is a separate topic rather than a recurring one.[4] So, whereas the theory of QC may be taught in lectures, it is not usually applied and incorporated into laboratory courses.[6] Perhaps the main reason for this is that there is no direct accountability or responsibility for the quality of results presented in student reports. It is uncommon to see laboratory lessons where students have to perform a follow-up to analyze the quality of their results.[7] This indicates that there is a need for practical lessons implementing QC tools and critical thinking that will help students to develop the skills needed both to apply QC methods effectively and to identify and solve problems.[8,9]

The development of critical thinking skills is not a simple task. Holmes et al.[10] report that "although critical thinking is a fundamental goal of science education, particularly the laboratory portion, the evidence indicates that is seldom, if ever, being achieved". They also suggest that students need to practice engaging in the critical thinking process themselves. In general, many educators and psychologists have pointed out that while the theory of critical thinking can be taught, it needs to be experienced first-hand,[10-12] which suggests that critical thinking has to be learned through practice. For laboratory lessons, critical thinking can be taken as a combination of knowledge and skills,[13] such as reasoning, drawing logical connections between observations and knowledge, and understanding the procedure used, which is used to take a decision about how to act on these results based on analysis tools that use appropriate statistics.[10]

The application of QC methodologies in laboratory lessons helps students to learn how QC is used to troubleshoot and repair faulty procedures from interception through to reporting.[4] It also may help students to develop valuable analytical judgement, helping them to learn how to interpret results.

CONTROL CHARTS IN LABORATORY LESSONS

One of the most fundamental and effective QC tools today are control charts and this is also the case in laboratory analysis.[6] Briefly, a control chart is a chart where the results of a measurement of a control sample are plotted against the number of samples.[6,14] When measurements are under control, only random variations are present in the chart and plotted results fluctuate around a control value, within certain control limits, called action limits (AL) and warning limits (WL). When a bias affects the experimental result obtained, the measurement falls outside the control limits and it is called an “out-of-control”. In this situation, the result is considered unacceptable because a systematic error has occurred during the application of the laboratory procedure and action is required to correct and solve the error before continuing with more analyses.[1,4,6,14] In general, control charts can be used to monitor the validity of a measurement over time, identify problems, and optimize laboratory procedures,[14] and their use is an important and powerful tool when performing routine tests. As indicated, their principal function is to distinguish between natural variability in a process and fluctuations attributable to an assignable cause,[15] however they can also be used by students to self-evaluate their experimental results.

The most common use of control charts in laboratory lessons has been to assess the trueness of student results and to identify systematic errors through the monitoring of control samples.[1,4,6-8,14-17] When an out-of-control measurement is detected, this result and the procedure by which it was obtained should be assessed in order to detect the source of the bias and to correct either the result or the procedure to avoid further bias. However, it is not common to allow students to work by themselves in this part since the methodology to study and solve these problems differs for each specific situation, requiring the application of scientific critical thinking skills and long periods of time to find an adequate solution. Moreover, common timetabling restrictions on laboratory lessons usually do not allow enough time to work on these skills. In some recent studies, a critical thinking approach has been incorporated to laboratory experiments to assess method effects on the results obtained by students.[6,7,15,16] These procedures are not only based on the simple visual inspection of control charts, but also on the application of other critical requirements, such as knowledge of the process and a common-sense approach to analysis, on the part of students in order to reach proper conclusions and to obtain results that are within control.[15] It has been found that the identification and discussion of real laboratory error sources by students themselves tends to be more educationally useful than putting in place the measures to eliminate these errors.[6]

The aim of this study is to demonstrate how the use of control charts can help students to develop thinking skills in laboratory lessons and to show them the importance of these methodologies in the assessment of laboratory results and to be able to optimize laboratory procedures and solve problems. The development of these skills by undergraduates is important as familiarity with process control is nowadays one of the most valuable skills required of newly hired employees in industry.[15,16]

METHODOLOGY

Experimental Procedure

A laboratory procedure for the determination of caffeine content in a commercial cola soft drink with a reduced and simple sample treatment before instrumental analysis by reversed phase HPLC was chosen in order to minimize the potential sources of systematic error and to simplify the parameters to be taken into account in a discussion session. Students were grouped in pairs and all groups of the same academic year had to evaluate replicates of the same lot of the drink.

To introduce the experiment, students were provided with an operating procedure describing the experiment and the working range required for the calibration standards (see Supplementary Materials). Each pair of students had to prepare and measure their own calibration standards. Sample treatment consisted of the elimination of carbon dioxide in an ultrasonic bath, a 1:5 dilution of the sample, and filtering through 0.45 µm filters before proceeding to the liquid chromatographic analysis.

Once samples and standards were prepared, the instructor explained to students how to use the instrumentation (liquid chromatograph). When the students finished their experiments, they had to perform calculations at home and deliver a report at the beginning of a discussion seminar session that was scheduled once all groups finished their laboratory sessions to discuss the results obtained and to introduce control charts.

Students' Background and Discussion Seminar

The laboratory lessons were developed for junior year biotechnology undergraduates. After all the students had finished their analysis, a discussion seminar introducing control charts was scheduled to evaluate the results and introduce thinking skills for solving laboratory problems. As laboratory sessions were scheduled weekly for each group, the joint seminar was performed between 1 and 5 weeks after students had performed their laboratory activities.

At the seminar, students were first given an introduction to control charts and how to use them. After this, each pair of students had to introduce, in a random order, their results in an Excel file that had previously been prepared for the display of control charts. The central point and upper and lower control limits of the charts were determined from previous experiments (n=15) performed by laboratory staff in the analysis of the same commercial drink with the same analytical procedure and instrument.

To enforce scientific thinking, it has been found that it is important to create an atmosphere in which students can ask the lecturer for help, but the instructor must not give them solutions.[18] Instead, the instructor can ask students questions that can help them to reach their own solutions. Moreover, it has been recommended to get students to work together as they can help each other.[18] For these reasons, in the proposed methodology all students had to discuss among themselves the possible sources of systematic errors that could have affected their results taking into account the experimental procedure applied. Once they had reached a consensus, a list was prepared and handed to the instructor. A new discussion was held with the participation of the instructor to assess whether the list was adequate or some modifications were needed. Once the list of probable sources of error was considered acceptable, students had to review their results with the control chart, and when a result was out-of-control they were required to check their reports and laboratory notebooks to try to find the possible reason for this anomalous result. Students were also required to propose changes in the laboratory procedure that could help to avoid these biases in future laboratory sessions.

RESULTS AND DISCUSSION

During the first year of application of the methodology (2016/17 academic year), five groups of students were scheduled and four pairs of students participated in each group (n=20). As the main objective of this study was to incorporate process thinking with evolutionary changes[9] in the way the students learn, the intervention of the laboratory lecturer was minimal during the preparation of the standards and samples, focusing only on the explanation of the instrumental technique that was to be used.

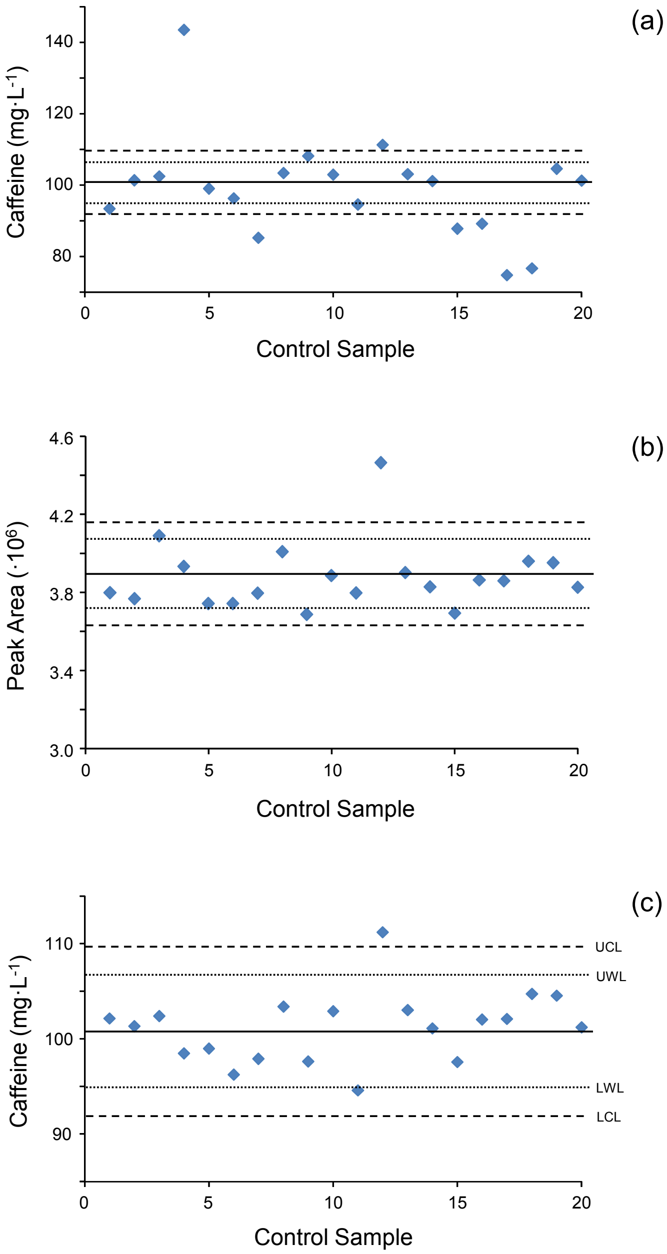


Figure 1. Control charts presented during the 2016/17 academic year: (a) Control chart of the caffeine concentrations presented by each pair of students in their preliminary reports; (b) Control chart of the signals obtained (peak areas) in the measurement of the treated samples; (c) Control charts of the final caffeine concentrations after correction of the bias that was detected. Each point corresponds to the reported result of a pair of students, plotted in a random order. Dashed lines correspond to the upper and lower control limits (UCL and LCL), dotted lines show the upper and lower warning limits (UWL and LWL)

As would be expected of junior students, no significant problems were detected with the sample treatment when they followed the operation procedure. However, it was observed that some students had problems with some basic laboratory skills, particularly with the calculations to prepare the calibration standards and the selection of the laboratory material required for the correct preparation of a solution since this information was not fully detailed in the procedure. This was surprising as students would already be expected to have acquired these basic skills. On interviewing the students, it was seen that they had only worked on these skills during the first laboratory course of their degrees in their freshman year. However, after this, they had usually found all calibration standards and reagent solutions pre-prepared in the laboratory, or they had worked with a detailed procedure explaining how to prepare these solutions, indicating the calculations and material required. On reviewing this matter with some teaching laboratory technicians, they confirmed that this was the case in many laboratory subjects.

Figure 1a shows the results reported by students during the control charts seminar of the first year of application of this methodology (n=20). As can be seen, seven pairs of students (35%, samples number 4, 7, 12, 15, 16, 17, and 18) reported out-of-control results. At this point, it was first explained to students that they should not consider an out-of-control result in the same way that they would consider an outlier in classical statistics calculations, where this value is usually taken as a mistake and is discarded for subsequent considerations. In process thinking it must be considered as important information that contributes to the knowledge of the process behavior.[9] Therefore, every result generates information that has to be evaluated and can be used to improve a process. For this reason, students were asked to create a list of parameters that could alter the results of their samples.

When students handed in the first list of possible sources of systematic errors that could alter the results of their sample they indicated that the systematic error was probably due to some failure of the instrument during the analysis. Surprisingly, the possibility of personal errors was usually not contemplated during this first step. When the instructor asked about what they considered to be systematic and random errors, many students associated one type of error to instrumental errors and the other to personal errors. For this reason, it was necessary to clarify this misconception before continuing with the methodology.

After this, students were required to take into account the procedure followed and to try to find which experimental steps or calculations could introduce systematic errors into the final results. To help the students, the instructor reminded them that all values reported corresponded to replicates of the same sample, which were analyzed following the same instrumental procedure, using the same instrument, and performing the same sample treatment in all cases. Therefore, they must take into account all the steps taken in the laboratory as well as the calculations applied to obtain the final result (e.g., weighing of a solid, dilution of a sample and volumetric material used, calculations using a dilution factor, …). Despite having this information, students had many problems at this point as, by their own accounts, this was the first subject where they had been required to work with these scientific thinking skills. As the intention was for these skills to be developed, the instructor assisted as little as possible during the discussion, only providing limited guidance by correcting those proposals that could clearly delay the process with limited or no benefit and without offering specific solutions. This methodology resulted in long discussion sessions, which was not surprising as it is known that data interpretation is one of the most challenging aspects of QC.[6] However, the results obtained were satisfactory and demonstrated that students are able to identify possible sources of systematic errors by themselves by applying previous knowledge acquired along their curricula if they are allowed enough time to reflect on the procedure used in the laboratory. In this case, students prepared a list of possible sources of errors that included: (a) loss of sample during sonication; (b) when measuring the volume of sample, taking an incorrect volume due to an incorrect use of the volumetric material; (c) performing an incorrect dilution; (d) error in the calculations when applying the regression equation, and (e) error in the calculations when applying the dilution factor. Despite this not being a complete list, it was considered sufficient to start the revision of their data.

After a first self-revision of their notebooks and data, no pair of students was able to find an explanation for their non-conforming results by themselves. With the help of the instructor, each of the possible sources of errors in the list was assessed individually.

Errors due to sonication were discarded because each laboratory group had sonicated a large volume of beverage and, therefore, each pair had taken its replicate sample after the beverage was sonicated. Students recognized that if a systematic error were to appear during the sonication, it should affect all samples of the same group in the same direction; but the control chart showed that the out-of-control results were randomly distributed between samples of different groups and that there were no groups with all their samples showing bias in the same direction.

When checking points (b) and (c) on the students' list, it was found that it was not possible to evaluate them as none of the pairs of students had recorded the specific volumetric material that they had used during their experiments in their notebooks. This helped to show students the need to record all the steps performed and material used in the laboratory in the notebook. Only a revision of the "theoretical volumes" reported in the notebooks was possible, and it was clear that the volumes of sample calculated for the dilution and the final dilution volume were correct for all pair of students.

Although some studies have reported that one of the most common source of systematic errors in student reports is calculation error,[6] no errors in either the calculation with each regression equation provided and the dilution factor applied in the calculations were observed. After the revision of all the parameters of the list, it seemed that it was not possible to identify the source of the bias detected. However, when all regression equations were reviewed together in the seminar, it was observed that there were some differences in the regression parameters given for some calibration equations. After a new discussion, it was confirmed that the calibration curve was a parameter that seemed to present some differences between the results reported, which was possibly because each pair of students had prepared their own calibration curve. At this point, some students suggested that it would be valuable to assess the readings obtained from the instruments for the diluted samples analyzed by each pair of students as this value is not affected by the calibration curve used and all students had applied the same dilution factor before the HPLC analysis, which resulted in equivalent diluted samples being analyzed by all students. A new control chart with the peak area obtained for each sample was drawn (Figure 1b), which showed a totally different trend to that of the concentration control chart (Figure 1a). Now, only one sample (5%) was found to be out-of-control. Interestingly for the students, this corresponded to sample 12, which was also out-of-control in Figure 1a, but it was the closest out-of-control result to the control-limits when the concentration control chart was evaluated.

The results obtained during the discussion session suggested to students that there were no instrumental errors due to the HPLC during the measurement of their samples and that bias seemed to be mainly due to systematic errors in some of the calibration curve equations. Therefore, it was decided to check the validity of the calibration curves of each pair of students. When they were asked to assess their calibration curves, only one pair indicated that their calibration was probably wrong (sample 4). Unfortunately, it was found that students only evaluated the validity of their calibration by reference to the determination coefficient (R^2) obtained. The group that reported an incorrect validation found an R^2 of 0.846, which was considered inadequate. All other groups considered their calibrations to be valid because they obtained $R^2>0.995$. However, when all the curves were plotted together on a graph, different slopes were observed. A statistical evaluation of the calibration equations confirmed that there were significant differences between the slope values given and eight calibrations (40%) had a significant systematic error. The *p*-values obtained suggested that six of these calibrations, corresponding to control samples number 4, 7, 15, 16, 17, and 18, could be considered large errors ($p<0.01$), all falling out of the action limits in Figure 1a. The other two calibrations, corresponding to control samples 1 and 9, were assigned as small errors ($p<0.05$), falling between action and warning limits in Figure 1a. These results confirmed that a systematic error causing the out-of-control results in the majority of reported results was associated with the use of inadequate calibration equations, probably due to an incorrect preparation of the standards. For this reason, all these students were required to recalculate their sample contents using a correct calibration equation obtained by another pair of students during the same laboratory session. The new results obtained now fell within the action limits (Figure 1c), except for control sample 12, which was the only one that was also found to be out-of-control when the peak areas were compared (despite its calibration slope being found to be correct). In the case of sample 12, the bias might be due to an error in the dilution of the sample, but it was not possible to confirm this from the information reported by this pair of students in their notebook.

After this session, students suggested that there was a need to emphasize the importance of basic laboratory skills when performing laboratory experiments. They also identified the importance of clearly recording the material used during the application of the procedure in their notebooks and of improving the control in the preparation of calibration standards.

Taking into account the problems found with basic laboratory skills during the first year of the application of the proposed methodology and the suggestions of students, some variations were introduced in the laboratory procedure in the following years. Consideration was also given to the fact that students must learn during their training that, in a collaborative environment, the results of the tasks that they perform can negatively affect the results obtained by others if they do not execute all steps and calibrate every instrument correctly. To reinforce this point, in later years the pairs of students worked in small collaborative groups, composed of three to four pairs of students, to prepare a common calibration curve. One of these pairs had to perform the preliminary calculations and suggest the material required for the preparation of the standards. The other pairs had to check and approve this information before proceeding to the preparation of the standards. Moreover, before performing any calculation, the validity of the calibration equations had to be verified by comparison with the other curves that were prepared by other groups of students.

This new procedure increased the laboratory time required for the preparation of the calibration standards and although it did not avoid incorrect calibrations being obtained, a significant improvement was achieved: it was found that of 14 calibrations performed during the following two years only three were incorrect (21%). Moreover, the requirement to perform the verification of the calibration parameters obtained for each group of students helped to detect the incorrect calibration equations before performing any sample calculation. As in the first year, when a calibration equation was found to be incorrect, it was substituted by a correct calculation obtained during the same laboratory session.

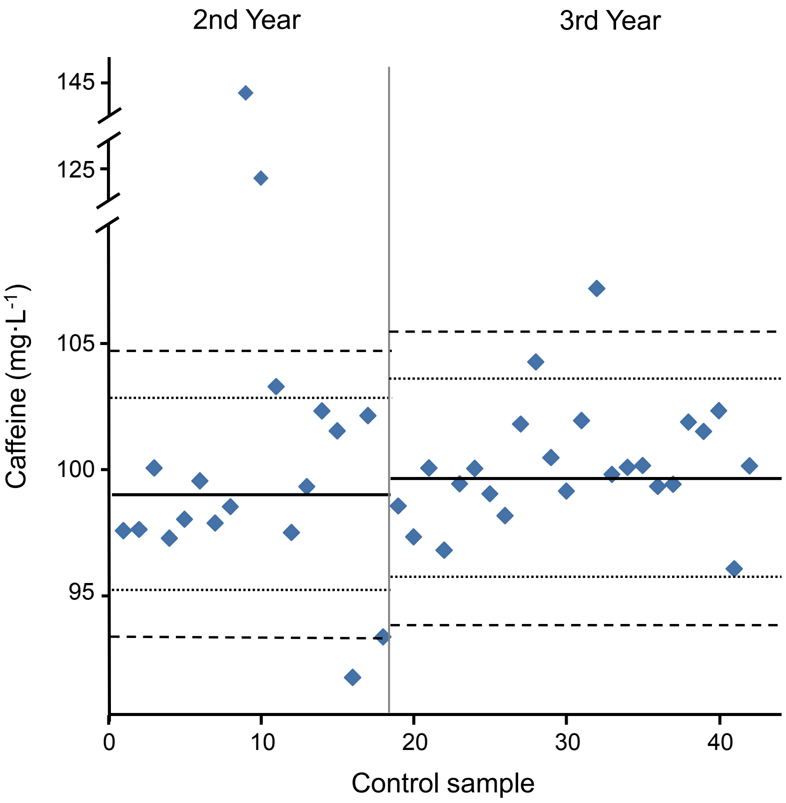


Figure 2. Control chart showing the results obtained in the 2nd year (2017/18, n=18) and 3rd year (2018/19, n=24). Dashed lines correspond to the upper and lower control limits (UCL and LCL), dotted lines show the upper and lower warning limits (UWL and LWL).

Figure 2 shows the control chart for the results of the next two years. It can be observed that despite the previous confirmation of the calibration equations used, there were some out-of-control results (n=3, 16.7% the second year; and n=1, 4.2% the third year), but these biases cannot be associated to systematic errors in the calibration. Since the new procedure required students to note down all the materials used in the notebook, it was possible to confirm the observation made during the first year regarding problems associated with basic laboratory skills. For example, the two out-of-control results giving the highest errors (controls 9 and 10 in Figure 2) were caused by an incorrect manipulation of class A volumetric glass bulb pipettes. Students recorded in their notebook the volume and type of pipette used, but when reviewing the results they commented that they had not taken into account that they were using pipettes with two marks when they were using it and so they emptied the whole volumetric content between the upper mark and the end of the pipette, which resulted in a systematic and non-constant bias in the dilution factor.

LEARNING ASSESSMENT

Once the methodology had been developed over a four-year period, a control assessment was prepared in the 2020/21 academic year. For this purpose, students performed the laboratory experiments and seminar in the same way that was done during the first year of the application of this methodology.

Before starting the control charts seminar, a pre-test was handed out to all students (n=61) containing two calibration graphs obtained from students who had previously taken the course (see Supplementary Materials for specific details). Students had to answer whether they considered the two calibrations to be correct or that some points should be eliminated before obtaining the regression equations. As was expected from students without previous knowledge of control charts and QC methodologies, all the students incorrectly based their answer on the coefficient determination obtained, which led 58 students (95.1%) to eliminate at least one of the standard results in one of the calibrations because it yielded an improvement in the determination coefficient from 0.973 to 0.993.

The data from the final-exam, three weeks after the seminar, students were asked the same question on being given the information that one of the calibrations corresponds to a verified and non-biased result used as a control. Only 17 students (27.9%) gave the same answer as in the pre-test, the 44 others (72.1%) now argued that the non-verified calibration presented a bias because the slope was very different. In a second question they had to determine the content of a control sample. The 44 students that had detected the bias in the previous step obtained a result that was within the control limits as they chose to use the regression equation from the verified calibration. In the case of the remaining 17 students, 15 of them recognized that an out-of-control result was obtained after making the calculations for the control sample and they re-evaluated their answers and finally suggested that a bias in the calibration equation was the cause of the error, and were able to solve it. Therefore, 96.7% of the students were finally able to identify the problem and achieve the learning outcomes of the exercise.

CONCLUSIONS

The results obtained in the present study have shown that the use of control charts in laboratory lessons is a useful tool for students to analyze the quality and validity of their experimental results. The use of a laboratory experiment in which all students analyze replicates of the same sample provides an opportunity to develop control charts for the class to use, which help students to detect and rectify errors using scientific critical thinking.

Before the control charts seminar, all the students participating in the study believed that their experiments had been performed successfully. However, when the control chart was displayed in the seminar it was seen that some results were unsatisfactory, and that in a real-world laboratory this would lead to an incorrect decision being taken. The use of control charts also helped students to understand that an out-of-control result does not necessarily indicate a mistake, as they had been taught in previous subjects in which outlier tests are performed to remove mistakes. In many analyses, the mistake is the consequence of a systematic error during the procedure applied, which can be corrected by applying critical thinking to find the source of such variability and correct the value. Moreover, when the source of the systematic variability is detected and is due to an assignable cause, it can be corrected in the following experiments, so eliminating the bias.

An important point detected in this study is that a significant number of students had problems performing basic operations in the laboratory, despite these skills being critical for the confidence that can be placed in the final result. It was found that due to time limitations in laboratory sessions and the limited number of them as a consequence of an overloaded curriculum (with a large number of subjects scheduled in each degree), the routine practice of basic laboratory skills, such as the preparation of reagents and standards, was usually avoided and laboratory sessions tended to be only focused on applying and demonstrating the concepts explained in lectures. Unfortunately, this problem with basic skills in the laboratory is not new and specific to the students participating in this study.[2] In general, it has been found that once basic skills are taught at preliminary stages of the curricula, they are taken for granted and little attention is usually paid to them in subsequent courses. However, it is important to remember that skills not only have to be taught, they also need to be practiced and reinforced. For this reason, employers in recent decades have become critical of graduates emerging from the university system without these basic skills. Different surveys have discussed the graduate skills required by employers and those that graduates have found to be of value when they start their working careers.[2,19,20] These reports show that science subjects should not only be based on core knowledge but also on experimental and analytical skills, which are often considered more important and useful than scientific knowledge.[19]

The methodology proposed here using control charts and scientific critical thinking has also helped to detect some misconceptions held by students that should be dispelled before they finish their degrees. First, it was found that students, and also many researchers, consider that a calibration only needs to be evaluated taking into account the determination coefficient, and any value above a predetermined one, usually 0.99, is considered as being a correct calibration. Second, when a systematic error is found, students tend to assume that this is something that must be eliminated without evaluating the source of the bias and without trying to correct it to avoid this problem in future analyses.

It is known that data interpretation is one of the most challenging aspects of QC [6] and the skills required cannot be adequately taught through lectures: students need to practice with real results to learn how to apply previously acquired scientific knowledge to solve biases. However, the connection between theory and implementation is not simple and fixed because the requirements are totally dependent on the specific case evaluated and may be totally different from one situation to another.

Unfortunately, students are not usually given the opportunity to develop critical thinking skills by themselves. The two most common situations that university students find themselves in are, firstly, that they do not train these skills in practically any subject, and, secondly, that when students do have the opportunity to work on these skill, they find that the instructor often introduces the specific source of bias to be tackled due to time limitations so devaluating the learning experience.

The methodology proposed here seeks to overcome these drawbacks by getting students to search for the source of the problem and determine how to resolve it. The results obtained suggest that this is indeed possible, but that it requires long seminars to be scheduled, which is often complicated due to timetable limitations. However, in our view it is essential to do this if our aim is to train fully competent professionals who genuinely have the skills required to detect and solve systematic errors in laboratory measurements.

It is of the utmost importance that students be allowed to develop and improve scientific critical thinking skills by themselves, even if this means that extensive periods of time have to be scheduled to perform the required discussion sessions with laboratory results. The experience obtained during this study has demonstrated that the time required for these seminars is at least twice the laboratory time required to simple obtain the results. Unfortunately, the design of many courses nowadays makes it very difficult to schedule the long sessions required to properly undertake this task. In our case, we were only able to find this extra time for the instructor and students outside of the scheduled teaching program.

ASSOCIATED CONTENT

Supporting information

Student handout

Details of Learning Assessment

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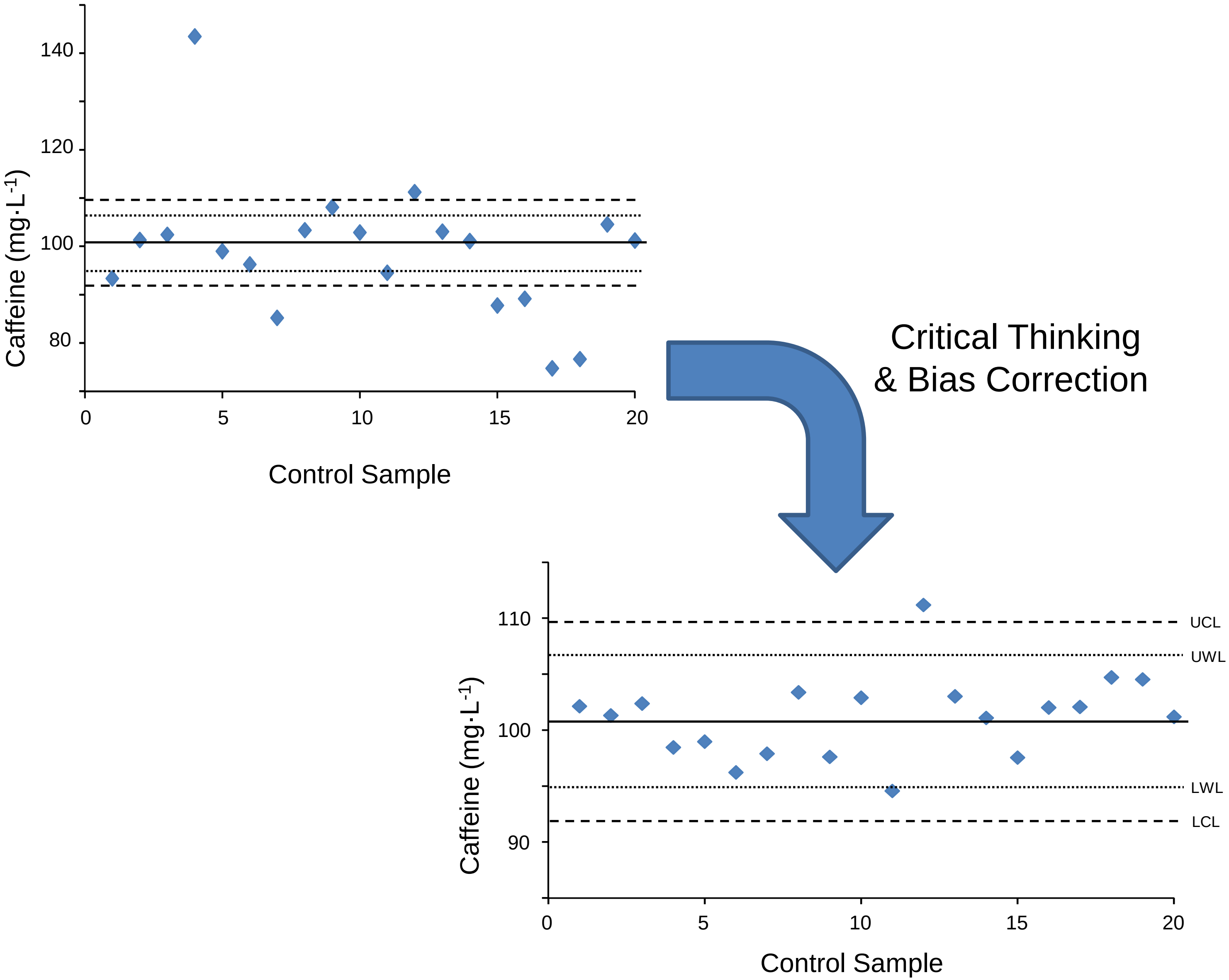
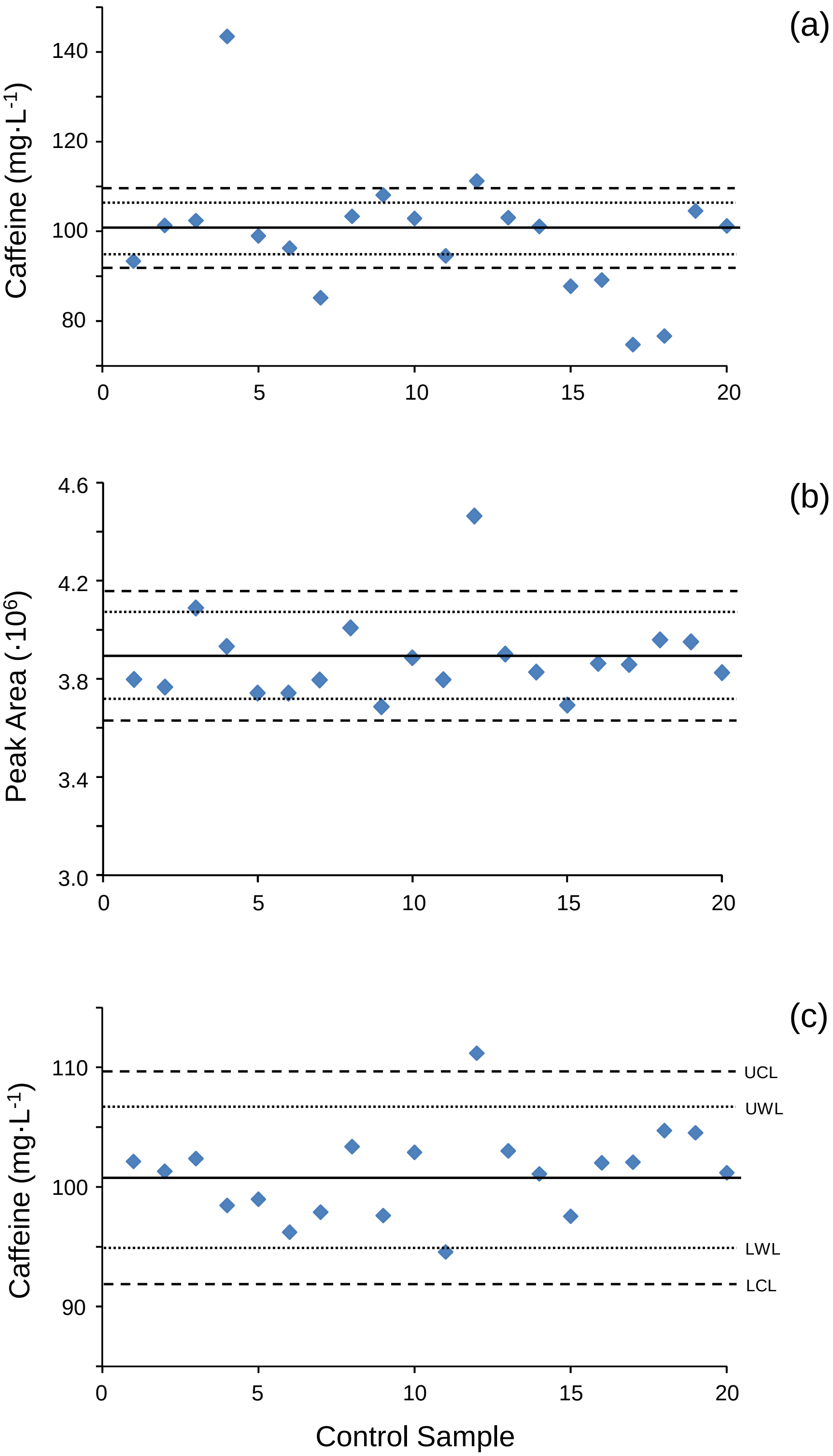
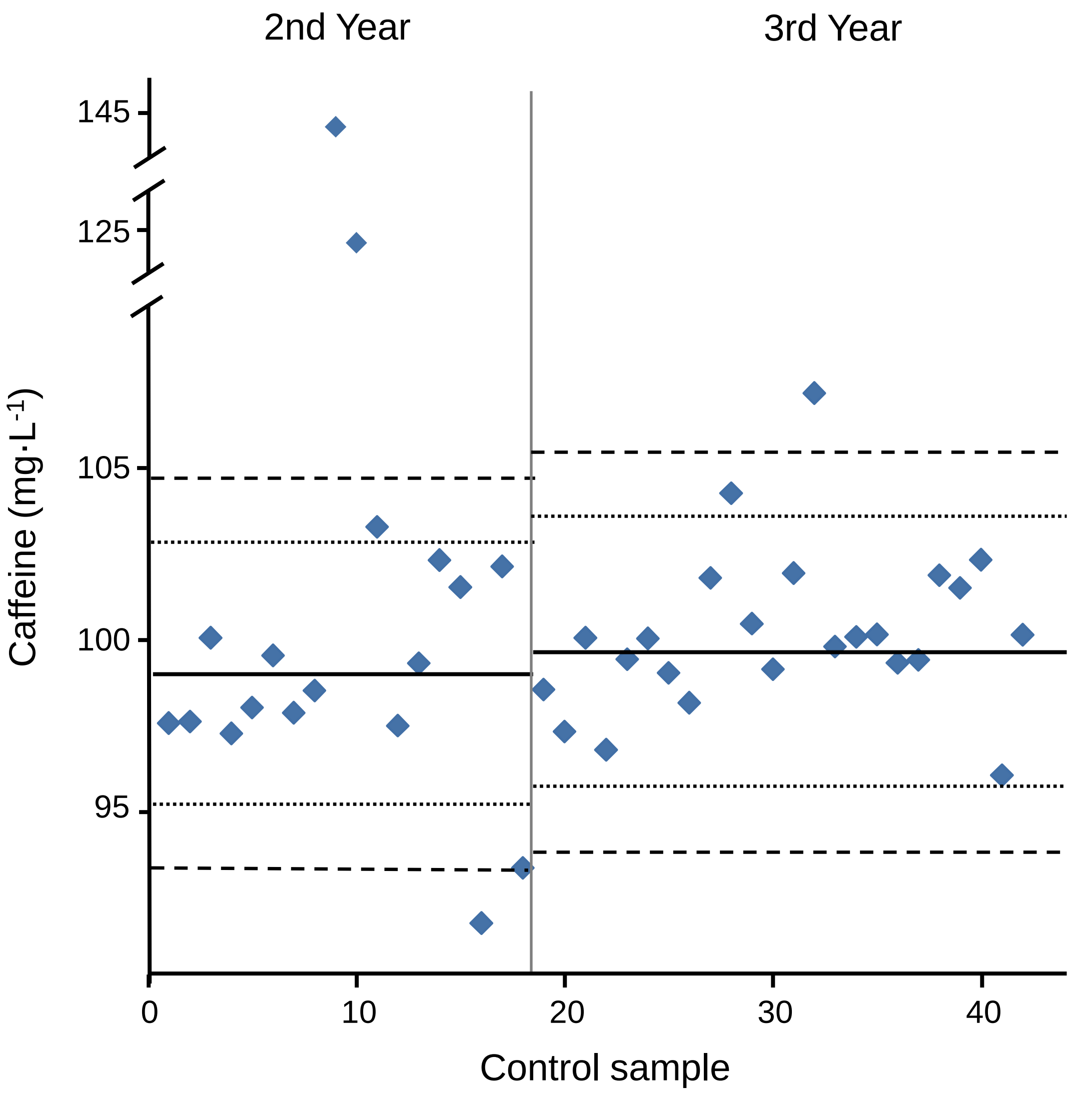

140
120
100
80
Caffeine (mg·L-1)
0
5
10
15
20
Control Sample
Critical Thinking
& Bias Correction
110
100
90
UCL
UWL
LWL
LCL
Caffeine (mg·L-1)
0
5
10
15
20
Control Sample


(a)
Caffeine (mg·L-1)
140
120
100
80
0
5
10
15
20
(b)
Peak Area (·10^6)
4.6
4.2
3.8
3.4
3.0
0
5
10
15
20
(c)
Caffeine (mg·L-1)
110
100
90
UCL
UWL
LWL
LCL
0
5
10
15
20
Control Sample


2nd Year
3rd Year
Caffeine (mg·L-1)
145
125
105
100
95
0
10
20
30
40
Control sample