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Communication

Unique Data Sets and Bespoke Laboratory Videos: Teaching and Assessing of Experimental Methods and Data Analysis in a Pandemic

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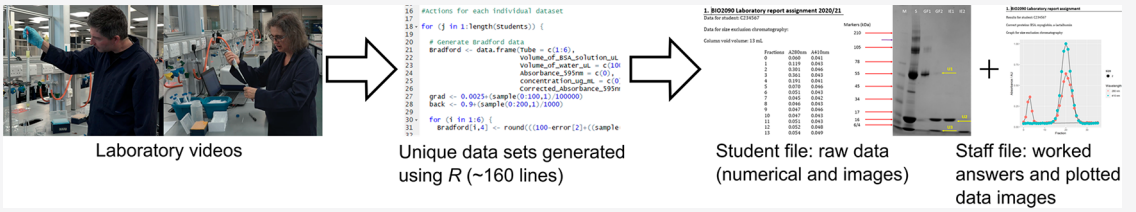

ABSTRACT: The COVID-19 pandemic necessitated the move to online teaching and assessment. This has created challenges in teaching laboratory skills and producing assessments that are robust and fair. Our solution was to use bespoke laboratory videos to provide laboratory training and to generate unique data sets for each student in coursework and exams. For assessments, *R* was used to produce student data packs comprising data and images, and associated staff answer files with plotted data and worked answers. In the new open-book online environment, this approach enabled us to create assessments that were the students' own work with no evidence of student collusion. We observed no difference in student performance for the coursework or exam: The mean and median marks for the course remained the same as in previous years.

KEYWORDS: *Second-Year Undergraduate, Upper-Division Undergraduate, Biochemistry, Laboratory Instruction, Testing/Assessment, Multimedia-Based Learning, Bioanalytical Chemistry*

At the University of Exeter, Biochemistry and Biological and Medicinal Chemistry degree students are taught within the Department of Biosciences. In the first term of their second year, these students take the compulsory module "Analytical Techniques in Biochemistry". This module teaches biological mass spectrometry, fluorescence techniques, separation science, immunological techniques such as enzyme-linked immunosorbent assay (ELISA), and cryo-electron microscopy. A substantial part of the module is spent in the laboratory (two 6 h and one 3 h sessions) and processing experimental data (Table 1, Figure 1). These activities are assessed through an extended laboratory report within term (coursework) and by performing calculations based on one of the experiments (in an end-of-module examination). Due to the UK COVID-19 restrictions, we were unable to run in-person laboratory classes. Consequently, we had two problems to address: How do we *teach* and *assess* the experimental part of our course?

A range of solutions have been proposed for moving in-person laboratories online in response to the pandemic (reviewed recently by Kelley[1]). Videos,[2−4] live online streaming,[5,6] simulations,[7−9] and virtual[10] or augmented[11] reality have been used as interactive lab replacements. Alternatively, students have conducted experiments at home using bespoke or commercial kits.[12−15] To teach data processing skills, students have been supplied with historical data sets,[2,5,7,16] with data generated by

Table 1. Course Topics and Assessments

Topic	Lab/Data Session	Assessed (Portion of Final grade)
Biological mass spectrometry	2 h data session	Coursework (15%)
Separation science	1 × 6 h lab +2 × 1 h Q&A	Laboratory report (35%); exam (optional, 15%)[a]
	1 × 6 h lab +2 h data session	Exam (20%)[a]
Immunological methods, fluorescence	1 × 3 h lab	Exam (optional, 15%)[a]
HPLC		Exam (optional, 15%)[a]
Cryo-EM		Exam (optional, 15%)[a]

[a]The exam has a compulsory data handling section (20% of final grade) with students completing an additional two out of four optional questions (30% of final grade).

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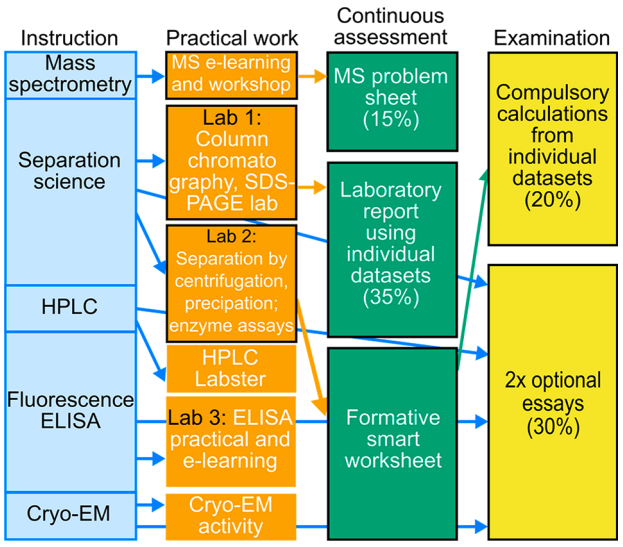

Figure 1. Schematic module overview. The module teaches five important techniques in analytical biochemistry. Each box is sized roughly in proportion to the time allotted for it in the module. Arrows indicate the path from instruction to practical work, continuous assessment, and examinations. The instruction, practical work, and continuous assessment work were supported by synchronous sessions. Activities that are not directly assessed (practical work) are in boxes without borders.

teaching assistants or instructors,[4,17] or have generated data themselves using simulations.[9] Assessing students fairly and robustly is challenging in an online environment. Students may be tempted to collude or cheat,[18−21] using third-party helper sites (e.g., Chegg) or online class chat groups.[22] Some institutions have responded by using proctoring software (e.g., RespondusLockdown).[22,23] Any assessment with a unique answer is particularly open to misconduct.[18] Our solution was to prepare *individual data sets* from historical student data sets (with associated worked answer files with data and image detail for staff) for both the laboratory report and for the examination.

OVERVIEW OF OUR KEY COVID-19 CHALLENGES

The assessed practical (lab 1) (Supporting Information) involves separation of a mixture of three proteins using size exclusion chromatography and ion exchange chromatography, and analysis of the proteins using SDS-PAGE and spectrophotometry of chromatograph eluates. Pre-COVID-19, eight proteins were used (Table 2). These proteins had been chosen for their physical properties (molecular weight, isoelectric point, number of subunits, absorbance at 410 nm) and price. Prepandemic, students would work in groups of three to four to collect data in the laboratory sessions. Data from this experiment were used to write a laboratory report (2,500 words, 35% of the module mark). Moving lab 1 online meant that we were not constrained to the original list of proteins. Two additional proteins that are not available commercially, GrpE (*E. coli*) and cytochrome c (*C. jejuni*), were added to increase the number of combinations of proteins available. This enabled us to move from three different protein combinations to eight (Table 3).

Table 2. Proteins Used for Lab 1

Number	Protein
1	Ferritin (horse spleen)
2	Catalase (bovine liver)
3	Bovine serum albumin (BSA)
4	Hemoglobin (bovine)
5	Myoglobin (horse heart)
6	α-lactalbumin (bovine milk)
7	Ribonuclease A (bovine pancreas)
8	Cytochrome c (horse heart)
9	GrpE (*E. coli*)[a]
10	Cytochrome c (*C. jejuni*)[a]

[a]Proteins 9 and 10 were added for 2020/21.

Table 3. Mixture of Proteins Used for Lab 1

Number	Protein Mixture
1	BSA, myoglobin, α-lactalbumin[a]
2	Catalase, myoglobin, α-lactalbumin[a]
3	BSA, cytochrome c (horse), α-lactalbumin[a]
4	BSA, cytochrome c (horse), GrpE
5	BSA, myoglobin, cytochrome c (*C. jejuni*)
6	BSA, ribonuclease A, cytochrome c (*C. jejuni*)
7	Catalase, myoglobin, cytochrome c (*C. jejuni*)
8	Catalase, ribonuclease A, GrpE

[a]Mixtures 1−3 were used pre-COVID-19.

The end-of-module exam includes a data handling section (40% of the exam/20% of the module). Students are asked to perform a selection of the calculations from lab 2 where students look at enzyme kinetics of two different enzymes and carry out a Bradford assay to ascertain protein concentrations. Historically, students have found this part of the exam challenging. To address poor performance, we introduced a bespoke Smart Worksheet (developed with Learning Sciences[24]) in 2018/19. This is an online tool that provides instant feedback which means the students cannot get "stuck" on their calculations. This allowed students to process their data and have their calculations and graphs checked automatically. Pre-COVID-19, this Smart Worksheet was used in a postlab session to carry out data processing in a supported environment and to facilitate additional feedback. In 2020/21, it was used completely online with a prerecorded video showing how to use it, and this remained available to students until shortly before the examination.

MOVING EXPERIMENTS ONLINE

With the undergraduate laboratory unavailable, bespoke videos[25] were created showing us performing each stage of labs 1 and 2. Students were provided with the original laboratory schedules (Supporting Information), asked to watch the relevant video, and asked to work through Learning Science simulations[26] of the techniques (e.g., running a protein purification column). Padlet[27] was used to collate student questions ahead of two timetabled Q&A sessions relating to each experiment. For the assessed practical, two briefing videos were provided. These explained how students should compose their report (as they had not previously been asked to write a report in this detail) and how to process the data.

These adjustments allowed us to provide our students with the required instruction. However, we faced two significant problems with fairly and robustly assessing students. First, students could not collect their own data to use in the laboratory report. We reasoned that supplying students with appropriate data sets would allow them to gain all the intended data

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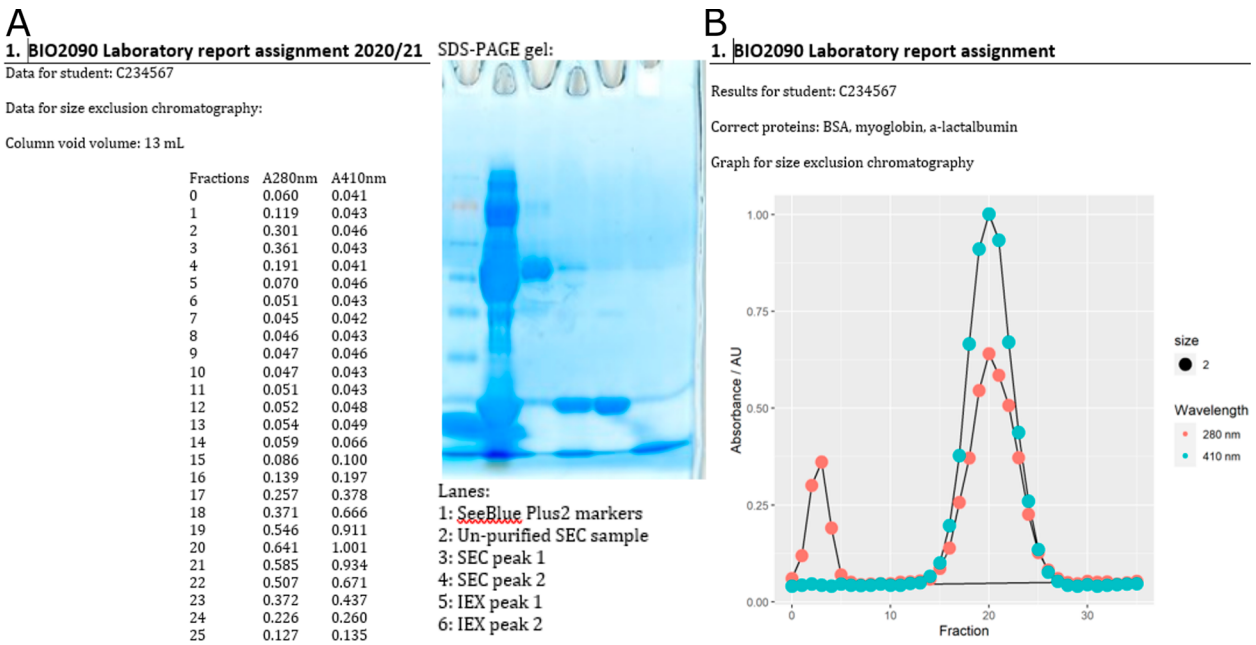

Figure 2. Example student and staff data packs for the laboratory report (lab 1). (A) Student packs contained all the data from the size exclusion and ion exchange columns plus an SDS-PAGE gel. (B) Staff files contained the plotted data and worked answers.

processing skills. We wanted to make sure that the students submitted work that was their own and not the result of collaboration. Second, the University of Exeter policies required that the end-of-module examinations would be noninvigilated. We feared that if a single set of data were used in the exam paper, it would be very tempting for students to "collaborate" and share their answers. In this paper, we outline our solution to these issues which was to generate *unique data sets* for students with corresponding answer files for staff.

Historical Data Sets

More than a decade's worth of student data sets was available for both experiments that could be drawn on.[28] These consisted of absorbance readings from chromatography column eluates and polyacrylamide gel electrophoresis (PAGE) images (lab 1), and Bradford data and absorbance readings from enzyme kinetics experiments (lab 2). It was essential that students were provided with interpretable (but not perfect) data, and we wanted data sets to be unique to ensure academic honesty for both summative assessments. For the formative Smart Worksheet (lab 2), a single historical student-generated data set was used. One instructor prepared a video using these data to explain how the Smart Worksheet operated. Students were provided with additional historical student data sets to process in their own time to develop their skills.

Unique Data Sets for the Assessed Practical Lab 1

For each protein mixture, one large protein (>30 kDa) and two smaller proteins (<30 kDa, one acidic and one basic) were selected. A historic SDS-PAGE gel image for each combination of proteins was required as we were unable to access the lab. Eight combinations of three proteins met all the criteria, compared to the usual three combinations used in previous years (Table 3). With the data provided and a firm understanding of the course material, students should be able to identify which three proteins were in their initial mixture.

Historical data were used to develop a mathematical model of the size exclusion and ion exchange column experiments. Data sets were generated using *R*[29] with approximately 160 lines of code required (Supporting Information). This produced a data set for the students (raw data plus SDS-PAGE image) and a worked answer file for staff (with data plotted and the answers) (Figure 2). All files were uploaded to the Virtual Learning Environment (VLE) with files identified by student number; we had no instances of students using an incorrect file.

ANOVA (Kruskal–Wallis test) was used to compare this year's cohort performance with those of the previous five years (Figure 3, Table 4). This showed no significant difference for four of the previous five years [2015/16, 2016/17, 2019/20 (p = 1); 2018/19 (p = 0.22)]. For 2017/18, there is a significant difference observed (p = 0.030): this cohort showed few weak reports, reflecting perhaps a strong year group who engaged fully with the assignment.

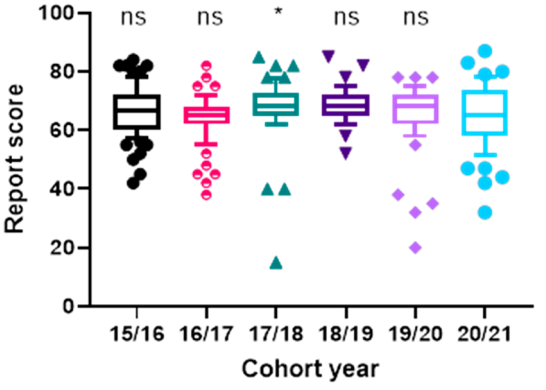

Figure 3. Box and whisker plot of laboratory report (lab 1) performance 2015/16–2020/21. Boxes show 25th–75th percentiles and the whiskers 10th–90th percentiles. Data from all years were compared to the 2020/21 cohort using the Kruskal–Wallis test. Significance levels: ns, $p > 0.05$; *, $0.01 < p < 0.05$.

Unique Data Sets for the Exam

Since the unique data sets had worked very effectively for lab 1, we decided to produce unique data sets for the online exam. Pre-

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Table 4. ANOVA (Kruskal–Wallis Test) Results Comparing Student Performance in Laboratory Report for 2015/16–2020/21

Academic Year	2020/21	*N*	Mean	SD	Median
2020/21		56	64.6	±10.7	65
2019/20	$p = 1$	57	63.5	±14.9	68
2018/19	$p = 0.22$	51	68.0	±5.5	68
2017/18	$p = 0.030$	49	67.7	±11.0	68
2016/17	$p = 1$	70	63.8	±7.9	65
2015/16	$p = 1$	74	66.2	±8.6	66.5

COVID-19, students sat for a 1 h invigilated end-of-module exam using a single data set for the data handling section. Due to the pandemic, the 2020/21 exam was a noninvigilated 24 h exam which would give students ample opportunities and time to check their answers and/or work collaboratively on this section of the exam. Consequently, we did not want to use a single data set for the data handling section and decided to create individual data sets for each student. Historical data sets from lab 2 were used to provide limits of reasonable student-derived values for the experimental observations. A model was developed to generate randomized data within these reasonable limits using *R* (Supporting Information). A set of 60 unique student data sets with associated worked answer files for staff including answers for each intermediary step in calculations were produced (Figure 4). Students downloaded their exam paper and their individual data set to use in the exam. This ensured that each student was required to work on a unique problem, reducing the incentive for students to collude. By labeling the data files with unique student numbers, it was again observed that all students used the correct data set.

ANOVA (Kruskal–Wallis test) was used to compare this year's cohort exam performance with the previous five years (Figure 5 and Table 5). There was no significant difference between the 2020/21 cohort and those from 2018/19 and 2019/20. However, there was a statistically significant increase in comparison to the 2015/16–2017/18 cohorts. This can be explained by the implementation of the Smart Worksheet in 2018/19 which has significantly improved the students' data handling skills.

Generating Data Sets Using *R*

Writing a suitable *R* script took a 4–6 h effort for an academic with limited *R* experience. Our annotated *R* scripts (Supporting Information) clearly explain each step and could be recycled to reduce this investment. We estimate that, for a similar experiment, 1–2 h would be necessary to repurpose our scripts. A first step was to use Excel to establish an appropriate model for data generation (Supporting Information). Excel was used as data can be readily linked to a figure allowing rapid feedback between changes and their effects. The model was validated

A

1. BIO2090 2020/21 January Examination

Individual data for student: C23456 for Question 1

Bradford standard curve data:

Tube	Volume_of_BSA_solution_uL	Volume_of_water_uL	Absorbance_595nm
1	0	1000	0.987
2	4	996	1.176
3	8	992	1.240
4	12	988	1.372
5	16	984	1.590
6	20	980	1.667

Sample Bradford data:

Fraction	Volume_of_sample_uL	Volume_of_water_uL	Absorbance_595nm
Homogenate, H	5	996	1.397
Cytosol, C	5	996	1.763
Mitochondria, M	5	996	1.535
Nuclear, N	5	996	1.327
30% ammonium sulfate	5	996	1.347
50% ammonium sulfate	5	996	1.717
80% ammonium sulfate	5	996	1.412

PGK assay data:

Fraction	Gradient_of_slope_AU_per_min
Homogenate, H	-0.227
Cytosol, C	-0.226
Mitochondria, M	-0.087
Nuclear, N	-0.148
30% ammonium sulfate	-0.038
50% ammonium sulfate	-0.058
80% ammonium sulfate	-0.273

B

1. BIO2090 2020/21 Exam Dataset

Data and answers for student: C23456

Bradford standard curve data:

Tube	Volume_of_BSA_solution_uL	Volume_of_water_uL	Absorbance_595nm	Concentration_ug_mL	Corrected_Absorbance_595nm
1	0	1000	0.987	0	0.000
2	4	996	1.176	40	0.189
3	8	992	1.240	80	0.253
4	12	988	1.372	120	0.385
5	16	984	1.590	160	0.603
6	20	980	1.667	200	0.680

Bradford graph: formula is y = 0.00341x + 0.0107

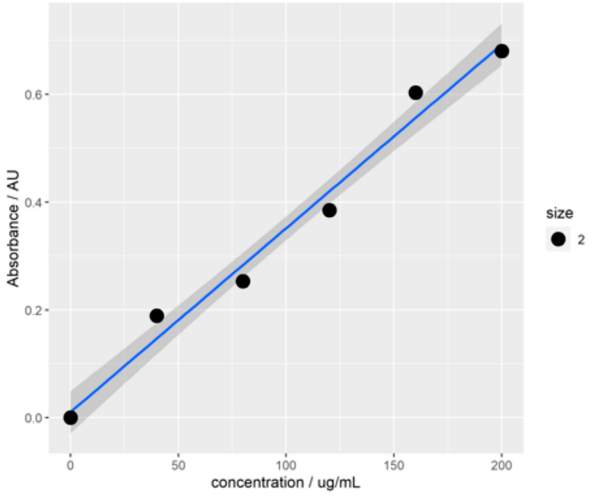

Figure 4. Unique data sets for the exam. (A) Unique data set used with exam paper. (B) Staff file with worked answers and example images. The shading in the graph indicates the 95% confidence intervals. Note that the corrected absorbance in panel B has been corrected to subtract the background reading at 0 μg/mL protein (tube 1 in the top table in panel A).

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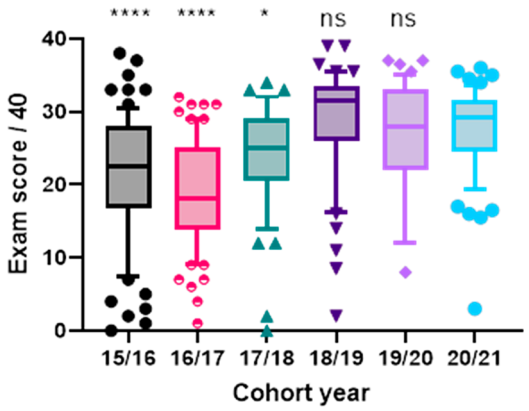

Figure 5. Box and whisker plot of the data handling exam performance 2016−2021. Boxes show 25th−75th percentiles and the whiskers 10th−90th percentiles. Data from all years were compared to the 2020/21 cohort using the Kruskal−Wallis test. Significance levels: ns, $p > 0.05$; *, $0.01 < p < 0.05$; ****, $p < 0.0001$.

Table 5. ANOVA (Kruskal−Wallis Test) Results Comparing Student Performance in the Data Handling Section of the Exam for 2015/16-2020/21

Academic Year	2020/21	*N*	Mean	SD	Median
2020/21		56	69.1	±15.1	73.1
2019/20	$p = 1$	57	66.2	±19.5	70
2018/19	$p = 1$	51	72.0	±19.4	78.8
2017/18	$p = 0.042$	49	59.5	±18.6	62.5
2016/17	$p < 0.0001$	70	46.8	±18.6	45
2015/16	$p < 0.0001$	74	53.1	±22.4	56.3

between the authors to ensure that the data generated were appropriate and no obvious errors made. Scripts were written in *RStudio* v1.1.456,[29] implemented through Anaconda 1.9.12.[30] Three nonstandard libraries were used: ggplot2[31] v3.3.4 (an easy to learn graphics package with excellent support), magrittr[32] v1.5 (a forward pipe function that makes the officer package easier to use), and officer[33] v0.3.18 (a package for manipulating MS Office documents through *R*; this was essential for producing the student and marker documents in an automated manner). The most important design principle is to save data that will be provided to students or markers as data frames where possible. Officer[33] can take a selection of data from a frame and present this as a table in a Word document. This allows for attractive presentation of the data to students with minimal code. In some cases, data frames were then manipulated to produce ggplot2 images. A second principle is to generate new files using officer where possible. This provides access to a wider range of style options with good documentation. An important advantage of using officer is that it produces files with students' numbers allocated automatically. These are ready to distribute to staff and students without further intervention.

DISCUSSION

The move to online delivery of both the experiments and assessments for this course presented challenges to provide an excellent education for our students and robust, authentic assessments.[34] The biggest concerns that we had were ensuring that each student's work was their own and that they were supported effectively. The laboratory videos we created meant that the students could see the techniques in detail and understand the workflow. Learning Science simulations[26] helped to consolidate the theoretical concepts. We have subsequently been able to get the students into the laboratory to perform sections of the assessed experiment, and the experiment videos were displayed on large screens to significantly improve our demonstration of the session work. Delicate handling steps were recorded in close-up, allowing all students to observe a detailed demonstration of key steps by an experienced experimentalist. Previously, all the students had gathered around a single demonstration rig; inevitably, some students had a poorer view, and students with impaired vision could rarely see the detail.

Others have used historical data sets to ensure academic honesty.[2,5,7] While we had extensive historical data available,[28] it was of varying quality. We wanted to ensure every student had good quality, interpretable, and nonambiguous data. The individual data sets created for the laboratory report (lab 1) enabled the students to gain experience in data processing and report writing even if they were unable to collect their own data. The opportunity to include two additional proteins in the simulated data packs permitted us to test understanding that had been challenging to achieve with reagents that are commercially available and sufficiently inexpensive to use in a moderate (n = 60) sized class. To support the students with their report, we held two live Q&A sessions, using Padlet[27] to collate questions. This year, we observed some of the highest scoring laboratory reports we had ever seen, but conversely some of the worst. We believe this stems from student engagement where approximately 20% of the class were highly engaged (these students participated readily in live sessions; VLE usage data showed that they engaged strongly with laboratory and instructional videos and the Smart Worksheet at the appropriate times) throughout the module whereas around 30% of the cohort did not engage until the last possible moment. Similarly, we observed this with student engagement with the materials for lab 2 assessed in the end-of-module exam: despite it being worth 40% of the exam (20% of the module), engagement (measured by VLE activity) was poor until the week before the exam. Consequently, many students did not gain maximum benefit from the support sessions. The observed average of 69% for this section of the exam demonstrated that the arrangements we made, especially the Smart Worksheet, were effective.

For the end-of-module exam, we had to consider that it would be open book and noninvigilated. Pre-COVID-19 we had a 1 h closed-book, invigilated end-of-module exam. We decided in the new online environment it was important that our examination was robust and that students worked independently. Student feedback was that they preferred a 24 h online exam, but we were concerned that the data handling section would be vulnerable to collusion[17−22] unless each student answered a unique question. This was the first time that an individual exam paper had been given to every student at our institution and required academic and administrative agreement on logistics. A standard exam paper was prepared with instructions to refer to the assigned data set. Students downloaded this from a folder released with the exam (Figure 4). All students successfully located their data on an examinations-only VLE site, and exam performance in this section of the paper was in line with the preceding two years, confirming that this approach gave a robust test of student performance.

The generation of the *R* code did take longer than setting conventional exams. The staff-worked answer files produced from the data sets were straightforward to use; generation of the worked answer files which included images as well as data was

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key to the successful deployment of this approach. Marking times for the laboratory reports were reduced by approximately 5 min per script (total 25 min) due to the plotted data in the worked answer files. In contrast, marking of the exam papers took longer (additional 5 min per script, total 10 min) and worked best using two screens/devices. If we deploy this method again, we will look at automating the marking for this section of the exam by getting the students to submit their answers via Microsoft Forms to provide an Excel compatible output that can be automatically marked. The *R* code lends itself most readily to numerical data. However, images can be incorporated into the documents produced. Our approach could therefore be used in disciplines that require specific symbols (e.g., advanced mathematics, organic chemistry) but would require careful exam design. This is something we will be exploring in the coming year for medicinal chemistry examinations.

Feedback from students showed that they really liked the laboratory videos and Learning Science simulations (both scoring 4.33/5 (Likert scale) in the end-of-module evaluation). However, they did not like the fact that they were unable to "check their answers with a friend" in either assessment. Overall, we were very pleased with the outcomes, and the mean mark for the module was in line with previous years despite the open-book, 24 h exam.

CONCLUSION

The generation of the *R* code enabled unique data sets for the students and worked answer file packs for staff to be generated for both coursework and exam. We would prefer students to collect and process their own data but continued social distancing rules may mean that this method is used in the future for the laboratory report. The opportunity to include additional reagents in simulated data that was not feasible to use in sufficient quantities in a laboratory class was very helpful. The laboratory videos substantially improved our ability to instruct students for laboratory sessions and will be reused for prelab preparation. If exams remain online, we will use unique data sets again as this approach has proven to be robust by limiting possibilities for collusion while maintaining academic standards.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c00853.

Lab 1 schedule (PDF, DOC)

Lab 2 schedule (PDF, DOC)

Example Excel Spreadsheet used to model data generation (XLSX)

Example *R* code (annotated) to generate unique data sets for lab 1 (laboratory report) (PDF, DOCX)

Example *R* code (annotated) to generate unique data sets for lab 2 (exam) (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

The R files used in this work are available at https://github.com/njharmer/Student-specific-data.

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REFERENCES

(1) Kelley, E. W. LAB theory, HLAB pedagogy, and review of laboratory learning in chemistry during the COVID-19 pandemic. *J. Chem. Educ.* **2021**, *98*, 2496−2517.

(2) Howitz, W. J.; Thane, T. A.; Frey, T. L.; Wang, X. S.; Gonzales, J. C.; Tretbar, C. A.; Seith, D. D.; Saluga, S. L.; Lam, S.; Nguyen, M. M.; Tieu, P.; Link, R. D.; Edwards, K. D. Online in no time: Design and implementation of a remote learning first quarter general chemistry laboratory and second quarter organic chemistry laboratory. *J. Chem. Educ.* **2020**, *97*, 2624−2634.

(3) Cabalsa, J. M.; Abraham, L. Exploring biochemical reactions of proteins, carbohydrates, and lipids through a milk-based demonstration and an inquiry-based worksheet: A COVID-19 laboratory experience. *J. Chem. Educ.* **2020**, *97*, 2669−2677.

(4) Donovan, W. J. The whiplash of a COVID-19 teaching pivot and the lessons learned for the future. *J. Chem. Educ.* **2020**, *97*, 2917−2921.

(5) George-Williams, S.; Motion, A.; Pullen, R.; Rutledge, P. J.; Schmid, S.; Wilkinson, S. Chemistry in the time of COVID-19: reflections on a very unusual semester. *J. Chem. Educ.* **2020**, *97*, 2928−2934.

(6) Petillion, R. J.; McNeil, W. S. Student satisfaction with synchronous online organic chemistry laboratories: Prerecorded video *vs* livestream. *J. Chem. Educ.* **2021**, *98*, 2861−2869.

(7) Dukes, A. D., III Teaching an instrumental analysis laboratory course without instruments during the COVID_19 Pandemic. *J. Chem. Educ.* **2020**, *97*, 2967−2970.

(8) Mistry, N.; Shahid, N. Design and delivery of virtual inquiry-based organic chemistry experiments. *J. Chem. Educ.* **2021**, *98*, 2952−2958.

(9) Perri, M. J. Online data generation in quantitative analysis: Excel spreadsheets and an online HPLC simulator using a Jupyter notebook on the Chem Compute web site. *J. Chem. Educ.* **2020**, *97*, 2950−54.

(10) Lu, Y.; Xu, Y.; Zhu, X. Designing and implementing VR^2E^2C, a virtual reality remote education for experimental chemistry system. *J. Chem. Educ.* **2021**, *98*, 2720−2725.

(11) Xie, C.; Li, C.; Ding, X.; Jiang, R.; Sung, S. Chemistry on the cloud: From wet labs to web labs. *J. Chem. Educ.* **2021**, *98*, 2840−2847.

(12) Caruana, D. J.; Salzmann, C. G.; Sella, A. Practical science at home in a pandemic world. *Nat. Chem.* **2020**, *12*, 780−783.

(13) Radzikowski, J. L.; Delmas, L. C.; Spivey, A. C.; Youssef, J.; Kneebone, R. The chemical kitchen: Toward remote delivery of an interdisciplinary practical course. *J. Chem. Educ.* **2021**, *98*, 710−713.

(14) Schultz, M.; Callahan, D. L.; Miltiadous, A. Development and use of kitchen chemistry home practical activities during unanticipated campus closures. *J. Chem. Educ.* **2020**, *97*, 2678−2684.

(15) Sansom, R. L. Pressure from the pandemic: Pedagogical dissatisfaction reveals faculty beliefs. *J. Chem. Educ.* **2020**, *97*, 2378−2382.

(16) Valle-Suárez, R. M.; Calderón-Mendoza, G. L.; Lanza-Sorto, N. A.; Ponce-Rodríguez. Teaching instrumental analytical chemistry in the framework of COVID-19: Experiences and outlook. *J. Chem. Educ.* **2020**, *97*, 2723−2726.
(17) Karayilan, M.; Vakil, J.; Fowler, D.; Becker, M. L.; Cox, C. T. *Zooming in* on polymer chemistry and designing synthesis of high sulfur-content polymers for virtual undergraduate experiment. *J. Chem. Educ.* **2021**, *98*, 2062−2073.
(18) Dietrich, N.; Kentheswaran, K.; Ahmadi, A.; Teychené, J.; Bessière, Y.; Alfenore, S.; Laborie, S.; Bastoul, D.; Loubière, K.; Guigui, C.; Sperandio, M.; Barna, L.; Paul, E.; Cabassud, C.; Liné, A.; Hébrard, G. Attempts, Successes, and failures of distance learning in the time of COVID-19. *J. Chem. Educ.* **2020**, *97*, 2448−2457.
(19) Norris, M. University online cheating—how to mitigate the damage. *Research in Higher Education Journal*, **2019**, *37* (November). aabri.com/manuscripts/193052.pdf (accessed 2021-11-01).
(20) Bilen, E.; Matros, A. Online cheating amid COVID-19. *J. Econ. Behav. Organ.* **2021**, *182*, 196−211.
(21) Dendir, S.; Maxwell, R. S. Cheating in online courses: Evidence from online proctoring. *Comput. Hum. Behav.* **2020**, *2*, 100033.
(22) Gonzalez, C.; Knecht, L. D. Strategies Employed in Transitioning multi-instructor, multisection introductory general and organic chemistry courses from face-to-face to online learning. *J. Chem. Educ.* **2020**, *97*, 2871−2877.
(23) Howitz, W. J.; Guaglianone, G.; King, S. M. Converting an organic chemistry course to an online format in two weeks: Design, implementation, and reflection. *J. Chem. Educ.* **2020**, *97*, 2581−2589.
(24) Learning Sciences. *Smart Worksheets*; https://learningscience.co.uk/smart-worksheets (accessed 2021-11-01).
(25) Wren, A. *Bitpod*; Bitpod.co.uk (accessed 2021-11-01).
(26) Learning Sciences. *Laboratory Simulations*; https://learningscience.co.uk/labsims (accessed 2021-11-01).
(27) Padlet. Padlet.com (accessed 2021-11-01).
(28) For lab 1, SDS-PAGE gels were imaged by graduate teaching assistants and distributed to students by instructors; the laboratory reports have been electronically marked for many years and remained on the marking server. For lab 2, student groups have supplied data to the instructor to be shared with the whole class to be used with the Smart Worksheet. Data sets have been retained to be provided to students who missed classes due to illness and could be given real but distinct data to work with. For these reasons, we had many historical student-generated data sets to use.
(29) Used in this work: *R* v.3.6.1 (R Core Team (2019). *R: A Language and Environment for Statistical Computing;* R Foundation for Statistical Computing: Vienna, Austria. https://www.R-project.org/ (accessed 2021-11-01). *RStudio v1.1.456*; www.rstudio.com (accessed 2021-11-01). A cloud-based version is available: https://rstudio.cloud (accessed 2021-11-01).
(30) Anaconda. *Anaconda Documentation*; https://docs.anaconda.com (accessed 2021-11-01).
(31) Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer-Verlag: New York, 2016. https://ggplot2.tidyverse.org/authors.html (accessed 2021-11-01).
(32) Magrittr. https://magrittr.tidyverse.org/ (accessed 2021-11-01).
(33) *Officer R Package*; https://davidgohel.github.io/officer/index.html (accessed 2021-11-01).
(34) Villarroel, V.; Bloxham, S.; Bruna, D.; Bruna, C.; Herrera-Seda, C. Authentic assessment: creating a blueprint for course design. *Assessment & Evaluation in Higher Education* **2018**, *43* (5), 840−854.

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