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ABSTRACT

Providing hands-on practical education without access to laboratories during the Covid-19 pandemic has required creativity and innovation. In this paper, co-authored by academic staff and students, we describe an at-home mobile phone-based 'spectrophotometer' experiment used in an introductory undergraduate biology course. Using colour picker apps, a smartphone can be used to quantify concentration, which was used to compare the strengths of different brands of tea. The protocol is designed to be low-cost and safe to perform outside of a laboratory. Students used the methods to learn important biochemical methods such as preparing dilutions, constructing calibration curves, normalising data and testing a hypothesis. We reflect on the experience of developing and using the protocol from a staff and student perspective, which highlights the advantages of this approach in terms of student independence and inclusivity. We also suggest alternative experiments that could be performed using the protocol. We encourage biology educators to think creatively about the possibilities for using mobile phones or at-home experiments in their teaching. Our experience suggests that at-home experiments like this protocol will have value even after the pandemic is over, particularly in terms of inclusivity.

KEYWORDS

Mobile phone; smartphone; spectrophotometer; biochemistry; inclusivity; COVID-19; student partnership

Introduction

The Covid-19 pandemic has required rapid and radical shifts in pedagogy. Practical science teaching has been a particular challenge for educators at all levels (Campbell et al. 2020). A variety of alternatives to laboratory-based practicals has been adopted within the Biosciences, including using laboratory simulations or videos, switching to data-driven projects, or virtual reality solutions (Francis 2020; Stafford et al. 2020; Delgado, Bhark, and Donahue 2021; Wilkinson, Nibbs, and Francis 2021). However, these digital approaches cannot replicate the physicality of experimental work, or the problem solving skills and resilience gained from laboratory work (Noel et al. 2020; Wilkinson, Nibbs, and Francis 2021). This paper describes an alternative approach to virtual experiments in the form of an 'at home' experiment that was used with a first-year undergraduate class of 130 students at the University of Hull.

This paper is written as a partnership by the academic instructor (KH) and students who performed the experiment. This partnership approach to writing recognises that students have expertise and insight into their learning that can only be captured by including them as authors in

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their own right (Cook-Sather, Healey, and Matthews 2021). This represents a shift in the staff–student relationship through the development of this activity. This project started with the instructor being in control through initial module design and delivery but evolved so that students became genuine partners in evaluation and dissemination (Bovill 2017). A relatively large number of student co-authors are included in our team to represent a diversity of opinions. Some sections of the paper are entirely written by the student author team, enabling their authentic voices to be heard on an equal basis to the staff perspective. Reflective sections from either staff or students are written in the first person to give authenticity of voice; the author of reflective paragraphs is clearly indicated in brackets at the start.

Ethical oversight for the project, including the co-author partnership, is provided by the University of Hull Faculty of Science and Engineering Ethics Committee (project references FEC_2021_85 and FEC_2021_93). Student co-authors and survey participants have provided consent for participation via an online survey platform. Co-authors have provided consent twice; once to participate in the writing process, and once to indicate that they consent to being named as authors on the final version of the manuscript.

Development of the protocols

[KH perspective] When considering how to replace laboratory classes for my first-year students, I wanted to provide students with a hands-on practical that they could do at home. I was unsatisfied with the prospect of entirely digital practicals, both in terms of the student experience and the fact that virtual labs cannot replicate the physicality involved in technical skill development. I also wanted to have an inquiry-driven exercise, as a wealth of literature supports the idea that collecting their own data and testing a hypothesis gives students greater insight into the scientific process and greater confidence in performing practical work (Healey and Jenkins 2009; Brownell and Kloser 2015; Bakshi, Patrick and William Wischusen, 2016; Wang 2017; Rowland, Lawrie, and Pedwell 2019). However, designing an 'at home' practical immediately placed a series of constraints on what could be done, particularly at scale. The method would need to be relatively cheap, safe to post out and for students to perform, and rely on minimal or readily available equipment. In searching for ideas, I came across the work of Kuntzleman and Jacobson (2016) who had developed a protocol for teaching Beer's Law using a mobile phone as a spectrophotometer. Under normal conditions, the students would be doing a spectrophotometer-based investigation into the effects of herbicides on photosynthesis (Dean 1996). I was therefore particularly interested by Kuntzleman and Jacobson's method as it opened up the potential for students to do an equivalent 'spectrophotometer' experiment. As such the method could potentially develop the same technical skills such as constructing a dilution series and a calibration curve, as well as testing a hypothesis. I anticipated that most students would own or have access to an appropriate device, so using a smartphone in this way had the potential for inclusive and authentic data collection independent of the laboratory.

While there is a wealth of literature on the use of mobile phones within educational settings, the focus of most studies is on either the potential for distraction by mobile phones (Goundar 2014; Shrivastava, Shrivastava, and Muscat 2014), or the opportunities that phones provide for mobile learning, remote access to content or as tools for increasing engagement (Lubega et al. 2004; Herrington and Herrington 2007; Fang 2009; Herrington et al. 2009; Jackson 2012; Bradley and Holley 2013; Lahlafi and Rushton et al. 2016). For example, many studies have shown the potential for mobile phones as audience response systems (e.g. Voelkel and Bennett 2014; Morrell and Joyce 2015). Mobile phone identification apps have also been used in field-based teaching, providing students with rich interactive content to support their learning (Thomas and Fellowes 2017). However, there has been less attention paid to the potential for using mobile phones as scientific instruments in their own right. Mobile phones carry a variety of sensors, including accelerometers, microphones and cameras, each of which has the potential to be used for empirical data collection (Mader and Smith 2011). There are several examples of smartphone-based methods within physics education. For example, Wisman, Spahn, and Forinash (2018) used a smartphone microphone to more accurately measure the time taken for tennis balls to fall to the ground, demonstrating that a falling object's horizontal velocity is independent of vertical velocity. Kubsch, Nordine, and Hadinek (2017) use thermal imaging cameras on some models of phone to illustrate concepts around energy loss.

The potential for using smartphone sensors for data collection has been relatively under-appreciated within biology education. This paper describes a method for using a mobile phone camera and colour picker app to turn the smartphone into a colorimeter or spectrophotometer, allowing the quantification of coloured solutions, based on the protocols of Kuntzleman and Jacobson (2016). This approach has been successfully used in a variety of chemistry education settings (Christodouleas et al. 2015; Moraes, Confessor, and Gasparotto 2015; de Morais et al. 2016; Kuntzleman and Jacobson 2016; Dangkulwanich, Kongnithigarn, and Aurnoppakhun 2018; Destino and Cunningham 2020; Kovarik, Clapis, and Romano-Pringle 2020). This paper illustrates the potential for this methodology within a biological context. Spectrophotometry is a commonly used method in introductory biology and biochemistry teaching laboratories. Typical introductory practicals allow students to quantify concentration of substances such as DNA, RNA, NADH, chlorophyll or a variety of dye molecules, and can be extended to measure rates of reaction (e.g. of NADH production by malate dehydrogenase in mitochondrial extracts). As such, being able to model the use of spectrophotometers with a smartphone has direct relevance to biological sciences. Due to the constraints of running this experiment as an 'at home' kit during the pandemic, students quantified the strength of tea produced by two different brands of tea bags, using colour as a proxy for strength. However, the methods would be appropriate for a wide range of biological investigations if students have access to readily available chemicals (e.g. acetone for chlorophyll extractions).

Protocols

This protocol was used for a first-year module 'Cells and Organelles' taken by 130 students at the University of Hull. This module is core for BSc Biochemistry, Biology, Zoology and Marine Biology, so has a wide variety of students with different levels of practical experience and confidence in the lab environment. Students with limited experience of practical work at school are more likely to find undergraduate practicals stressful and challenging (Hubbard et al. 2017), so the protocols were developed to walk students through the methods step-by-step. Written and video instructions were provided, and multiple online drop-in sessions were provided for support. Although the protocol is designed for first-year undergraduates, with appropriate support it would be equally useful for high-school pupils, or possibly for the general public at e.g. science festivals. Step-by-step protocols are freely available online (Hubbard 2021a, 2021b). Instructional videos are freely available via YouTube (Hubbard 2021c).

The method was designed to be low-cost and low-risk, so could be done either at home or in a classroom with minimal equipment. Development of the protocol was done in the instructors kitchen to ensure it could be done at home, and all instructional videos were filmed in the home environment. Students were provided with 20 × cuvettes, 8 × plastic pipettes, 5 × 50 mL plastic centrifuge tubes (falcon tubes), scissors, white card, a marker pen, sellotape and a template for making the cuvette holder. The only item students required other than the kit contents and a camera phone is therefore a kettle and a mug for making cups of tea. Even the kettle could be dispensed with, either through use of a microwave or by brewing teabags in cold water over an extended time period. There is therefore no need for the experiment to be conducted in a laboratory in this case, students performed the experiments at their homes or university halls of residences. Rather than pulling data from the student record system, addresses were collected via a quiz on the module course page, where students were informed that they could choose their current address and the way they wanted their name presented. This reduced the risk of 'outing' students who may have different identities at home than on campus. This method did result in delays in posting for students who submitted addresses late or incorrectly, which did cause additional burden for technical staff. Students who did not submit addresses or whose kits were lost in the post were provided with an example dataset to write up.

When performing the experiment, the first task is to set up the phone as a colorimeter. The cuvette holder is constructed from white card as per the instructions and is then positioned relative to the phone and a white background (Figure 1A). The experiment is best performed in a bright well-lit room – daylight is better, or a domestic lamp can be used to reduce the internal shadows within the cuvette holder. To avoid the cuvette moving between measurements, it should be sellotaped the cuvette holder to the table/work surface. The ColorPicker app is then opened, and the phone positioned so that the digital 'picker' lines up with the middle of the cuvette (Figure 1B, C). The colour picker app needs to give numerical Red, Green and Blue (RGB) for quantification. 'Colorpicker' for iPhones (Heynen 2019) and ColorGrab for Android phones (Loomatix 2021) are recommended, both of which are freely available to download.

Once the phone is set up, experimental work can begin. The first stage is to verify that the ColorPicker app can detect different concentrations by constructing a calibration curve. For the 'tea' experiment a cup of tea is made up in a set volume of water and for a defined length of time (e.g. 50 mL water, brewed for 1 minute). A dilution series is then constructed from 100% to 5% tea to give a range of concentrations. The dilutions are measured using the ColorPicker app and a calibration curve constructed. As RGB values are scaled such that darker colours give smaller values, the calibration curve with raw RGB values has a negative relationship that may be confusing for later data analysis (Figure 2A). To give a positive relationship between concentration and normalised RGB value (Figure 2B), the data can be normalised through the following calculations:

$$Measured\ Green\ value\ for\ an\ empty\ cuvette = 204$$

$$Measured\ Green\ value\ for\ a\ tea\ sample\ dilution\ (25\%) = 86$$

$$Green_{Normalised} = 1 - (Green/255)$$

$$For\ pure\ white : Green_{Normalised} = 1 - (255/255) = 1 - 1 = 0$$

$$For\ pure\ black : Green_{Normalised} = 1 - (0/255) = 1 - 0 = 1$$

$$For\ the\ tea\ sample : Green_{Normalised} = 1 - (86/255) = 1 - 0.337 = 0.663$$

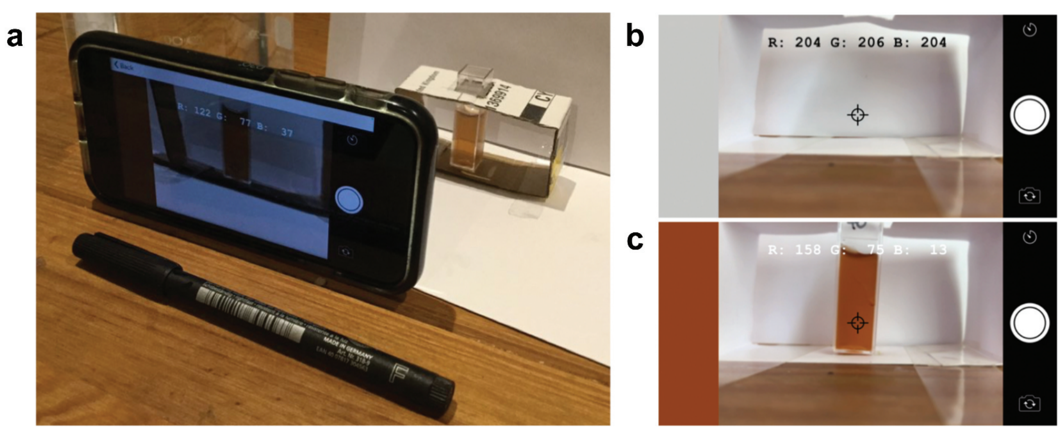


Figure 1. Mobile phone colorimeter setup. A: relative positions of the phone, cuvette holder and cuvette. B: Screenshot of the setup without a cuvette (R:204,G:206,B:204). C: Screenshot of the setup with a cuvette of 50% diluted tea (R:158,G:75,B:13). Screenshots are from the instructional video available via YouTube (Hubbard 2021c).

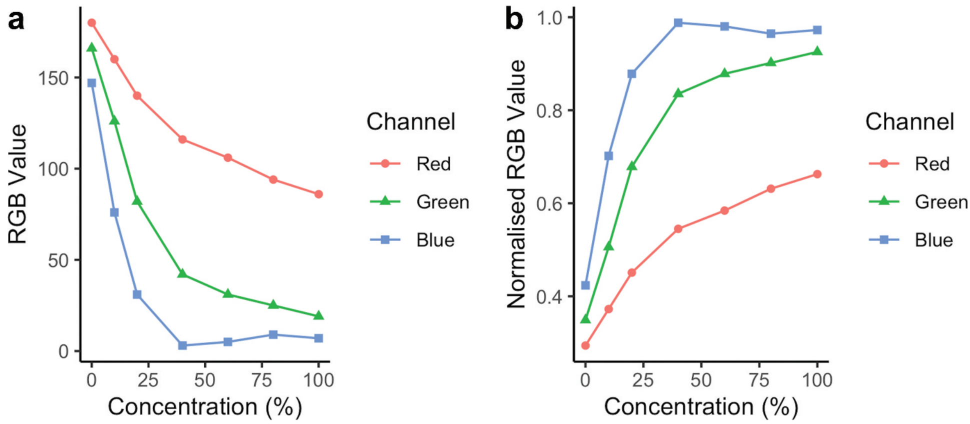


Figure 2. Calibration curves for dilutions of tea. A: raw RGB values for each of the three channels, resulting in a negative relationship between concentration and RGB. B: Normalised RGB values for the three channels, giving a positive relationship.

Measurements taken from an empty cuvette in the cuvette holder did not reach the maximum possible white value of 255, but were between 150 and 255 depending on the amount of ambient light. The calculation could therefore be adapted as follows to include the use of an empty cuvette as a blank, better mimicking the setup for a spectrophotometer. Alternatively, the blank could be a cuvette containing water (i.e. the 0% sample).

$$Green_{Normalised} = 1 - (Sample_{\ Green}/Blank_{\ Green})$$

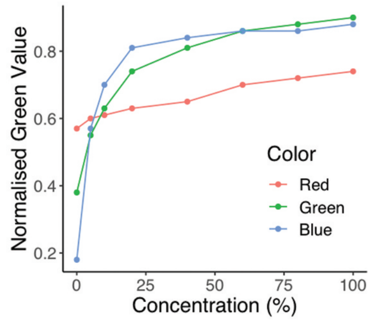
$$For\ the\ tea\ sample: Green_{Norm} = 1 - (86/204) = 1 - 0.421 = 0.578$$

While some students found this calculation challenging due to a lack of mathematical confidence, the benefits of having a positive relationship on the calibration curve make it a worthwhile step for subsequent analysis. It also introduces the idea of data processing and normalisation that will have value for later scientific training.

Once the calibration curve has been generated, some methodological decisions need making. The first is to decide which colour is most appropriate for future measurements. Sometimes the calibration curve shows that the values saturate at quite low concentrations (e.g. the blue channel in Figure 2B). Alternatively, there might not be much change in value over a range of concentrations for a given colour channel, making the assay relatively unresponsive to concentration. The most appropriate colour is that which gives the strongest relationship with concentration that does not saturate at low or intermediate concentrations. In the example given above, Green was chosen as the most appropriate channel for future measurements as it gave the best compromise between dynamic range and saturation, although some saturation occurs at concentrations above 50%. Alternatively, Red could be chosen as the curve that best approximated a straight line, i.e. did not saturate at higher concentrations. Students were not given marks for choosing the 'correct' line but were expected to justify their choice in their write-ups. The appropriate dilution factor for subsequent measurements also needs determining, given that the signal saturates at high concentrations. In online support sessions, the shape of the calibration curves was discussed and highlighted that dilutions in the linear portion of the curve were most appropriate to use. In the case in Figure 3, a dilution of 20% was deemed most appropriate as this was in the dynamic portion of the curve, i.e. the signal had not yet saturated.

Once these methodological choices have been made, experimental measurements can commence. In this case, students were asked to determine whether there was a difference in the strength of tea made by two different brands of teabag, using colour as a proxy for strength. As this experiment was also being used to introduce two-sample t-tests, students were advised to collect

Calibration Curve						
Concentration of tea	Mean RGB value (n = 3)			Mean Normalised RGB value (n = 3)		
	Red	Green	Blue	Red	Green	Blue
0%	111	157	209	0.57	0.38	0.18
5%	102	115	110	0.6	0.55	0.57
10%	100	94	76	0.61	0.63	0.7
20%	93	66	49	0.63	0.74	0.81
40%	90	48	41	0.65	0.81	0.84
60%	77	36	37	0.7	0.86	0.86
80%	70	31	35	0.72	0.88	0.86
100%	66	26	30	0.74	0.9	0.88



Comparison Experiment					
Type of tea	Replicate No.	Green Value	Normalised Green Value	Mean	Std Dev
Teabag	1	102	0.60	0.59	0.019
Teabag	2	103	0.60		
Teabag	3	100	0.61		
Teabag	4	104	0.59		
Teabag	5	112	0.56		
Loose leaf	1	153	0.40	0.39	0.050
Loose leaf	2	168	0.34		
Loose leaf	3	162	0.36		
Loose leaf	4	156	0.39		
Loose leaf	5	136	0.47		
T-test results: t = 8.39, d.f. = 8, P < 0.001					

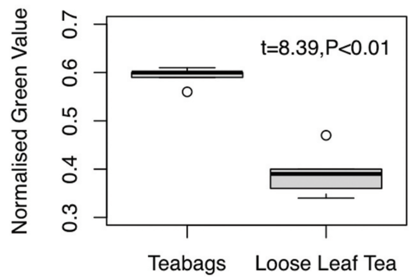


Figure 3. Example of student collected data for calibration curves and comparisons for t-test.

at least five replicate measurements for each of the two conditions (brands of tea bag). Sampling strategy is part of the experiment that students could have autonomy over, within the context of any formal statistical analysis planned for the data.

Alternative potential experiments

Students were given the option of designing their own experiments using the setup. For example, a protocol was developed that used acetone-based nail polish remover to extract chlorophyll from leaf samples, which could then be quantified in a similar way. Step-by step instructions for the chlorophyll experiment are available freely online (Hubbard 2021b). The flammability of acetone made it unsuitable for posting, so students wanting to do the chlorophyll experiments at home needed to purchase the nail polish remover, hence this protocol was not compulsory. In a lab setting where postage is not an issue, the chlorophyll method opens up lots of potential student driven biological research questions e.g. comparing sun and shade leaves, old or young leaves, leaves from different species of plants. Some students in the cohort did choose to purchase nail polish remover to allow for chlorophyll-based experiments. For example, one student compared the chlorophyll content of an aquatic species with a terrestrial species, while another compared different types of salad leaves. Other possibilities at home might be to measure the solubility of spices such as paprika in different solvents (e.g. water, vodka, nail polish remover). With access to a laboratory, the range of experiments can be expanded to any chemical that produces a coloured solution; pH sensitive dyes would lend themselves to this method. It may even be possible to determine the activity of biological extracts; for example DCPIP-based assays of photosynthesis should be possible, using the decolorisation of the blue dye as an indicator of photosynthetic rate.

Evaluation

Survey results

To gather their opinions on the experiments, all students on the module were asked to complete an online survey. 41 out of 130 students completed the questionnaire (31.5% response rate), so the results should not be assumed to reflect the views of the whole class. Responses were obtained from students on all four degree programmes on the module (Biochemistry 6, Biology 10, Marine Biology 19, Zoology 6). One student reported that they had not received their kit despite having submitted their address so was removed from analysis, leaving 40 responses. Not all questions were compulsory, so percentages are calculated relatively to the number of students answering the question.

Thirty-two out of 40 (80%) students said that they had enjoyed using the at-home kits, while seven (17.5%) said that they had not enjoyed it. Around half of the students reported that they had no problems using the kit at home (22 out of 40; 55%). Of those who reported problems, the most common issue was with controlling the lighting or position of the phone (seven students), followed by difficulties in following the instructions (four students) and lack of space at home to perform the experiment (three students).

'The lighting in my house is awful and I have no light that would give me the natural white colour. On top of that my natural lighting became dark because of the weather so it's a practical that really needs natural lighting and also somehow needs you to eliminate all possible shadows'.

'The only real problem was making sure the colorimeter was taking its reading from the exact same spot of each sample every time. I overcame this by placing my phone in a set position and drawing a square on a piece of paper so I knew exactly where to place my sample'.

One student reported that acetone dissolved the cuvettes; this was not an issue that arose when testing the acetone extractions during method development. This suggests that different brands of nail polish remover have different chemical compositions which had not been anticipated, and indicates tests for any reactions between the cuvette plastic and nail polish remover should be performed before experiments start.

Students were also asked how confident they felt about practical work before and after using the kit (Figure 4). 18 out of 38 (47%) students reported that their confidence had stayed the same, 17 (45%) said that their confidence had increased and three (8%) reported a decrease.

Student reflections

To give further insight into what it was like to carry out the experiment, the student authors have reflected directly on their experiences through this section. Other than minor edits for readability, these sections are entirely authored by students in the first person, so are authentic reflections on the experiments described.

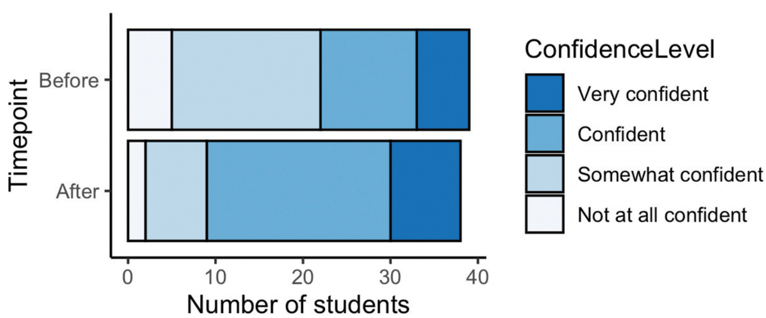


Figure 4. Confidence levels of students before and after using the at home kits. Shifts in responses were statistically significant (Chi-square test: $\chi2 = 8.85$, df = 3, p-value = 0.031).

What we learned from the experiment

[Students] Carrying out the tea experiment was a new learning opportunity which we saw as beneficial. Due to Covid-19 many had not been in a lab setting yet but this provided opportunities to do practical work. A package was sent in the mail, and we did the practical at home. The practical was backed up with short YouTube videos that explained everything clearly and helped consolidate any questions that were posed by students (Hubbard 2021c). The use of the home practical kits helped put the things we learned in lectures into action and helped us reinforce principles and facts that we learned. It gave the students that respond to hands-on education a chance to immerse themselves into the work and gain a deeper understanding of the module. This form of learning had both positives and negatives.

The experiment itself taught us how to use different software such as the 'colourpicker' app which gives RGB values of a particular substance the camera lens is aimed at. Additionally, we were able to acquire more knowledge on how to perform hypothesis tests digitally. The test also provided us the ability to construct more complex graphs, and understand the scientific process more (how the tea strength is different and how significant our results were).

Many students felt that there was also opportunity for independence and exploration. There was freedom to choose different research questions, which required different methods. This independence was key to developing understanding of basic protocol and lab technique. It also allowed students to practice skills previously learnt through online resources and enabled students to develop their coding skills further by practicing using R studio to analyse the data. Most students had not used a standard colourimeter before, never mind being aware of the ability to use their mobile phone as one. Additionally, conducting this experiment provided a hands-on aspect to the development of data analysis skills. Previously we had only analysed artificial or pre-collected datasets, as opposed to collecting and analysing our own data.

Doing the experiment at home

[Students] The coronavirus pandemic has really tested the deliverance of module material, in particular how lab experiments could be performed. As practical competency could not be observed by lecturers, new ways of engaging had to be made. Most experiments would be difficult to complete at home. This is as everyone has different circumstances/may not have scientific apparatus to complete complex experiments. With this test, it was easy to complete due to no hazardous or unobtainable materials being needed. Basic plastic equipment could be posted out and reach students based in the UK within a few days.

Some people performing the practical experienced louder, busier homes due to the pandemic. This could have affected the practical's results or their understanding of the concept the practical was pushing. Some people struggled with filling the cuvettes to the same spot every time, and did not feel confident to ask the lecturer for help. Not everyone has grasped the use of Microsoft Teams or email for contacting staff as it is a new concept of learning. Another problem people ran into was keeping the lighting the same. Lighting changed over the day and would have affected the results the longer the experiment went on. Another variable that could not be controlled was keeping the phone in the same spot every time we took a measurement. Some phones needed charging after only getting through half of the experiment, the movement of the phone would have made the result slightly inaccurate.

If we were to perform the experiment again, we would have taken the initiative to be more independent, not just using the tea samples provided. We would ideally test something we have a greater interest in, for example marine biology students could potentially test chlorophyll content of marine phytoplankton. We believe more experiments at home would be advantageous as you can learn and apply what you have learned to come up with scientific conclusions on everyday problems – like what tea brand to buy. If costs are low, and material is put in place to support the completion, we would have no qualms with future at home experiments – it would be good to do in conjunction with more complex lab experiments that must be done on campus.

We have successfully managed to complete the investigation without the need for full professional laboratory equipment. Many of us think that performing the test in a lab would be more beneficial. This is because of the potential experience and knowledge that we could gain by working in professional settings. However, the at-home method allowed students to experience laboratory practice. The experiment allowed us to be independent by testing the theory without a lecturer or peer support but to follow our initiative alongside instructions. On the other hand, it allowed us to form support groups and connect with other students in our department. Some of us believe that the supervision of someone who already performed the test would be beneficial as it reduces the risk of completing it incorrectly.

Lessons Learned – Student Perspective

[Students] Carrying out the experiment at home allowed us to gain a basic understanding of the lab protocol and the technique we would have used had we attended the lab session on campus. Therefore, although it was not in a scientific lab, we still got to develop our lab skills. We learnt that the at home practicality really benefited those who cannot get to campus sessions because of childcare and travel issues or mental/physical health. It was also a good idea for those students who have anxiety-related issues around working in a lab and feel overwhelmed in similar environments.

Reflecting on what we did, we think that overall the experiment was successful and should be carried out again in the future with a few changes made. First, we think that a few socio-economic presumptions were made regarding what students had to provide. All students needed an adequate workspace to carry out the experiment and for some students this was hard to find due to having siblings and other family members who also required the use of the same space. As well as this we had to have access to a good-quality phone that supported the use of the colour app we had to download as part of the experiment. Thinking about future experiments it is important to consider that not all students have access to a high-quality mobile and some may not have a mobile phone at all. This would potentially put them at a disadvantage as they cannot collect their own data and therefore cannot partake in the experiment.

Another change we feel that needs to be made is the flexibility of the experiment; whilst this experiment was partial to change there was not enough flexibility for people to adapt the experiment to fit their interests and relates to their course. Regarding carrying out the experiment, most students found the process straightforward; however, some students did find the methods confusing so for future experiments it would be effective to carry out the experiments in a trial group of students that can provide feedback on the methods and accessibility of the experiment before it is distributed to all students on the module. This would mean that the instructions can be re-written and more/less equipment can be included if needed.

In relation to the equipment, some students we spoke to mentioned how it was largely made of plastic material and therefore not environmentally friendly. The kit will most likely not be reused so if home experiments were to continue students should not be given new equipment every time and instead be expected to use previous material and only be provided with new if the experiment requires something not used before. Alternatively, possible eco-friendly equipment that is available should be distributed if possible.

Staff reflections

[KH] From an instructor point of view, the main challenges with the activity were to do with running it remotely and asynchronously, rather than the methods themselves. This is reflected in the student observations above. Given that students have highlighted places where the instructions could be clarified, for future iterations the instructions will be co-written with students to minimise misunderstandings or confusion. Developing the method to run in kit form was challenging, particularly given that I was unable to post out any liquids or chemicals. Finding a hypothesis to be tested using the method that could be done at scale, relying on the postal service and ensuring that students could work safely at home placed significant limitations on what could be done. I agree with the students that it would have had more impact as an exercise if it was adapted to allow for a greater range of experiments. If students collected the kits or used them in the laboratory this would allow for the distribution of chemicals, enabling a greater range of experimental options. I am also struck by the student comments around the amount of single-use plastic required. This is a fair observation, but the kits probably used less plastic than the equivalent laboratory practicals. The sustainability of laboratory plastic use is a real issue (Madhusoodanan 2020), and I would be interested to collaborate with students further to address this within our broader practical portfolio as it is something our teaching and technical team should be more aware of.

[KH] Given the limitations of the situation, I am really pleased that most students enjoyed the exercise and found value in it. I was impressed by the quality of calibration curves that most students were able to produce, which demonstrated that they had been accurate in preparing dilution series even with plastic pipettes rather than using Gilson pipettes as they would have done in the lab. I was also pleasantly surprised by how many students in the survey said that their confidence had increased as a result of doing the kits; given the constraints we were under I wasn't expecting this response to be so positive. I am also struck by how inclusive the students found the exercise to be, so will be including it as an alternative to laboratory practicals for students with ill health or extreme social anxiety. For future use of this kit in appropriate contexts, I will encourage students to adapt the methods to investigate more biologically relevant hypotheses (e.g. chlorophyll concentrations), and to repeat the protocols to optimise the accuracy and reliability of data. This optimisation is particularly relevant for the lighting conditions, which was the most common source of technical difficulty experience. The survey responses and student reflections mean I am confident that the kit can be an appropriate inclusive replacement for practicals in certain situations, allowing students to meet learning outcomes or competencies that depend on practical skills in an alternative environment.

Conclusion

We found that using a mobile phone-based spectrophotometer method was an effective teaching strategy within the context of undergraduate biology. While there are improvements that could be made to the protocols and range of experiments that could be done, most students saw value in the activity. Moving forward, 'at home' practicals could be carried out again in the future but they should not replace labs on campus. Instead, they could be used as an inclusive alternative to on-campus practicals for those students who cannot get there or are unwell. Alternatively, they could be used as a pre-campus activity to allow a basic understanding before attending campus, which would decrease anxiety and increase overall confidence in carrying out lab techniques. The advantages of at-home experiments identified means that there is merit in exploring the potential of at home kits, even after the pandemic is over. The mobile phone protocol is one example of how at-home kits can teach students valuable laboratory skills. We encourage other biology educators to think creatively about other methods that might be appropriate for at-home investigations, and to collaborate with students to deliver quality practical training even if the laboratory is unavailable.

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