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Thinglink and the Laboratory: Interactive Simulations of Analytical Instrumentation for HE Science Curricula

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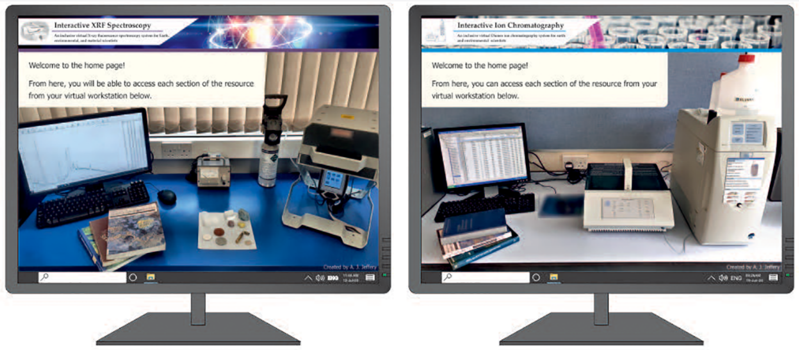
Welcome to the home page!

From here, you will be able to access each section of the resource from your virtual workstation below.

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From here, you can access each section of the resource from your virtual workstation below.

ABSTRACT: Access to laboratory facilities and associated instrumentation represents a major barrier to learning in physical science education, due to constraints introduced by limited time and financial resources, cost of acquisition, and health and safety requirements. Virtualized laboratories offer some mitigation of these problems but may also introduce further problems such as limiting discussion and collaboration, inhibiting development of physical skills, and reducing engagement. This study aims to evaluate the effectiveness of virtual simulations of analytical instruments for applied science student learning and teaching. Two virtual instruments (X-ray fluorescence spectrometer (XRF) and an ion chromatography system (IC)) were assembled on the Thinglink online virtual platform, with background theory, detailed animated instructions, and simulated data collection capabilities. The two simulations were disseminated to teachers and learners, with subsequent feedback gathered *via* questionnaires and four one-to-one interviews. Results showed that feedback was extremely positive from all users, with many expressing excitement for the accessibility and inclusivity implications and the freedom to engage asynchronously. Users found them to be high quality, highly accessible, and inclusive resources but generally felt that their application as supporting information would have greater benefit than using them in a standalone fashion. The most prominent concern was the time required to create materials. Study implications suggest that the style of online virtual learning resource presented here is viewed as beneficial by learners and teachers alike, if planned to be as efficient as possible and delivered as a supplement to physical equipment learning. The application of additional online resources to broader groups should be the subject of further investigation, with the potential benefits for academic performance being of utmost importance.

KEYWORDS: *First-Year Undergraduate, General, Second-Year Undergraduate, Analytical Chemistry, Laboratory Instruction, Distance Learning, Self Instruction, Internet, Web-Based Learning, Laboratory Equipment, Apparatus, Spectroscopy, Chromatography*

■ INTRODUCTION

Modern physical science-related curricula (including Chemistry, Earth Science, Life Science, Forensic Science, and Environmental Science, among others) are predominantly dependent upon access to laboratory facilities and associated instrumentation, albeit to varying degrees.[1−3] This may take the form of necessary skills such as chemical analysis, microscopy, or material characterization, to name but a few examples.[4−7] In each case, this dependency on facilities and instrumentation introduces a potential barrier to the achievement of intended learning outcomes and the development of key skills, which must be overcome, either at the institutional level or at the personal level of either the educator or the learner.[8] For example, aspects of analytical chemistry (and associated educational challenges) might be found in various areas of education, such as Medicine, Material Science, Metallurgy, Environmental Science,

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Geoscience, and Forensic Science.[9−14] As such, some aspects of learning in these fields rely heavily on access to high-end analytical instrumentation such as spectrometers and chromatography systems. In this example, the ability for learners to engage with these analytical instruments provides not only the opportunity to gain hands-on experience and develop fundamental practical and analytical skills, which link strongly with employability, but also a potentially collaborative learning opportunity with peers, allowing them to develop their social and scientific communication skills.[15] Nevertheless, access to this form of learning comes at an inevitable cost; barriers to learning include the financial costs associated with the acquisition and day-to-day running of instrumentation, the management of resources, availability and access of equipment, and the awareness of and ability to provide reasonable adjustments for learners with specific educational needs.[16,17] Of these, the former is managed at the institutional level, whereas the latter two are arguably shared between the level of the institution and the individual teacher/lecturer. Similarly, learners may be required to conduct chemical analyses of various materials, including synthesized compounds, solutions, metals, and natural materials such as rock, soil, and water, for which they will need to conduct instructed sample preparation and subsequent guided analysis. This is dependent upon access to laboratory space, staff time, and instrumentation, which, due to the costs of acquisition, may be restricted to a single instrument (e.g., X-ray fluorescence spectrometer).[18,19] There may also be health and safety considerations, which preclude unsupervised use of instrumentation, requiring further resource allocation to permit access. All these factors inevitably act as a barrier to learning by restricting the numbers of learners able to access the instrument at one time, due to space, staffing, physical laboratory constraints, or health and safety protocols.

Virtual laboratories are a form of E-learning[20−28] that attempt to simulate[29−32] or even provide remote access to[33] laboratory facilities, are a common means of alleviating these difficulties, and have been applied to chemistry education,[34−42] as well as other areas of higher education.[43−51] The benefits of this approach are well-constrained[52] and include cost effectiveness, geographical range, and learner control,[53] and many educational institutions have dedicated considerable resources to its implementation.[54] Virtualized laboratory resources inevitably vary in scale and scope, from compact materials designed for specific learning outcomes[55] to materials designed in full 3-D environments and covering a considerable range of academic material.[49,56,57] The potential benefits of this style of learning resource can be divided into three key themes: (1) development of key skills (e.g., knowledge and understanding, inquiry skills, practical skills, perception, analytical skills, and social and scientific communication)[56,58,59] and academic performance, (2) learner motivation and wellbeing,[60] and (3) efficient resource management.[61] Despite these positive points, virtual laboratories are not without their recognized faults and difficulties: potential negative factors include: (1) discouragement of learning using real instrumentation, (2) discouragement of discussion and collaboration between learners, (3) reduced interaction between learner and educator, (4) increased risk of plagiarism, (5) reduced development of hands-on skills, and (6) time investment required to create material.[62−64]

In this study, we focus primarily on the final, and perhaps most commonly cited, negative point associated with virtual laboratories—namely, the time, effort, and expertise required to create them. We employ the education technology platform called Thinglink to demonstrate how educators could create unique and bespoke viable virtual laboratory resources with little expertise or training. The Thinglink platform is based around the augmentation of images and videos to create interactive, visual learning experiences for users to utilize.[65] The software platform allows the user to upload images and add a variety of "hotspots", which, when clicked, can provide additional images, text, audio files, or links to other images. The user may also upload 360° digital still images or videos, which can be augmented in the same manner. When a resource has been completed, it can be disseminated to potential learners *via* a link, which will provide immediate access. Although there are some restrictions on the maximum number of visitors to an individual project, this is dependent upon the form of license held, which needs only to be held by the educational establishment not the learner. As a learning platform, Thinglink has numerous applications and has gained attention in recent years in teaching and outreach.[66,67] There are particularly powerful applications for Thinglink in the education setting, particularly for virtual fieldwork, an area of teaching that has considerable potential for increasing accessibility of the field and has gained particular relevance in light of the limitations imposed by the COVID-19 health crisis.[68−70] Resources can be as generic or as specialized as required, and their application to other areas of the curriculum, which are dependent upon students being physically present in a given location at a specific time (e.g., petrography, laboratory-based geochemistry), would have similarly considerable benefits to teaching in this field. One of the biggest potential strengths of the Thinglink platform relative to other means of producing virtualized laboratories is its simplicity and flexibility. The platform requires minimal training to use, and the only raw materials required for content creation are images and/or videos that can be combined with audio files, all of which can be generated with minimal cost. For example, all of the photographs utilized in the resources presented in this study were generated using a smartphone camera. All of the audio files were downloaded from readily accessible free-to-use websites, and all videos were created using MS Powerpoint. Furthermore, Thinglink is a browser-based platform and does not have any considerable requirements in terms of hardware (an Internet connection is required). These minimal requirements and open approach provide a resource that allows the user to apply the platform in any way they choose, producing a learning resource that fits their own needs and those of their learners, at any scale of their choice (e.g., individual experiment vs complete simulation of an analytical instrument), and using whatever materials they prefer. There are no constraints on the user other than their own creativity.

As such, this study aims to evidence the application of two Thinglink-based, virtual laboratory learning environments as complementary higher education educational tools for undergraduate, postgraduate taught, and research students, which may empower educators to mitigate or reduce some of the above barriers to laboratory-based learning. The specific objectives of this paper are therefore:

1. To explore and report on the potential of the Thinglink online platform as a means of deploying high quality, image/video-based, interactive learning resources, which simulate and supplement analytical instrumentation and other laboratory-based learning.
2. To evaluate the applicability of these virtualized learning environments when employed as a supplement to higher

Let's have a look at a simplified view of the individual components inside the instrument and see what they are for:

Analyte	Conc. (%)	Error (%)
Sb	1.639	0.036
Sn	11.985	0.113
Cd	0.067	0.013
Pd	0.025	0.012
Ag	5.205	0.061
Mo		
Nb		
Zr		
Bi	0.622	0.045
Pb	77.208	0.722
W		
Zn	0.324	0.013
Cu	0.088	0.014
Ni		
Co		
Fe		
Mn		
Cr		
V		
Ti	0.086	0.027
P	0.957	0.075
Si	1.737	0.216

Figure 1. Example pages from Resource 1: (A) the title screen, which acts as a welcome to the resource, (B) the home page, from which the user can access each section of the learning resource, (C) an example of an interactive page, which allows the user to explore the various internal components of the instrument, (D) an example analysis page, designed to simulate actual use of the instrument, from which users can select a sample to analyze and learn more about setting the instrument up and calibrating it, (E) an example analysis screen in which users can view and select the sample they wish to analyze, and (F) an example data readout screen for an analyzed sample, including access to more detailed spectral information. All corporate logos are masked.

education within the physical and chemical sciences, taking into account factors such as the time investment required to produce resources, the impact on inclusivity and accessibility, and their perceived value in the eyes of both learners and educators.

■ METHOD AND IMPLEMENTATION

Creating Learning Resources in Thinglink

Two online asynchronous (allowing users to work through them in their own time and at their own pace) learning resources were produced and are termed as Resource 1, X-ray fluorescence spectroscopy (XRF), and Resource 2, ion chromatography (IC).

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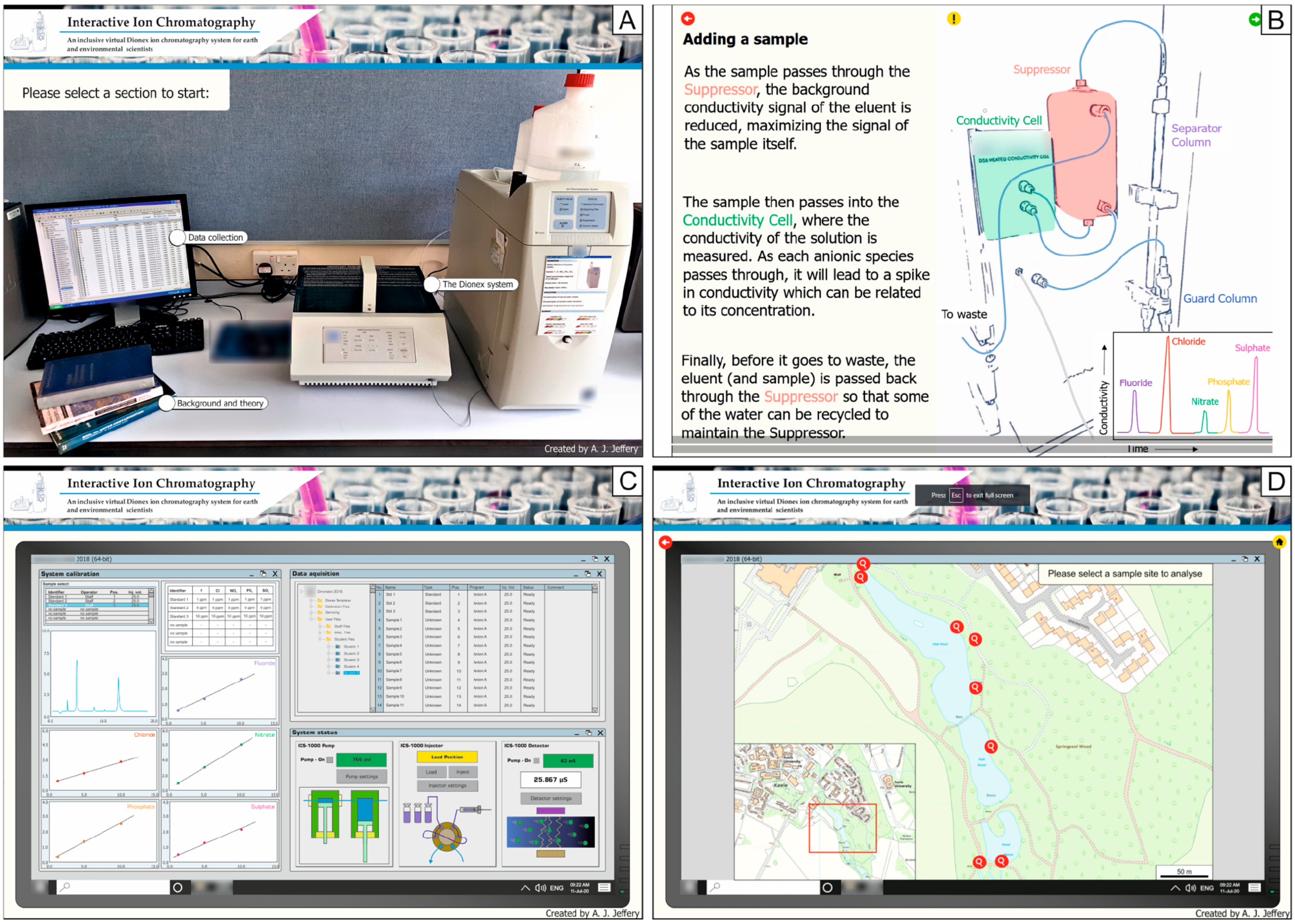

Please select a section to start:

Adding a sample

As the sample passes through the Suppressor, the background conductivity signal of the eluent is reduced, maximizing the signal of the sample itself.

The sample then passes into the Conductivity Cell, where the conductivity of the solution is measured. As each anionic species passes through, it will lead to a spike in conductivity which can be related to its concentration.

Finally, before it goes to waste, the eluent (and sample) is passed back through the Suppressor so that some of the water can be recycled to maintain the Suppressor.

Please select a sample site to analyse

Figure 2. Example pages from Resource 2: (A) the home screen, which acts as a main hub for the resource and allows users to access the various sections of the resource, (B) an example animation, which guides the user through the process of sample introduction and analysis, (C) an example analysis screen, designed to simulate analytical software, from which users can select samples to analyze or learn more about instrument setup or calibration, and (D) an example sample selection screen, from which users can use a map to view different sampling localities prior to analysis. All corporate logos are masked.

These instruments were selected for virtualization on the basis of their high usage for teaching as part of multiple curricula (e.g., Chemistry, Environmental Science, Geography/Earth Science). Each resource was constructed using photographs of the instrumentation, alongside digital videos created in Microsoft Powerpoint. These included images of the instruments in their local environment to provide material for a simulated workstation, as well as images and diagrams designed in vector drawing software. Due to the highly visual nature of the resources, great effort was made to ensure that the images and videos were of high quality.[71,72] These images and videos were subsequently uploaded to Thinglink and augmented with "hotspot" locations, which provide a series of structured pathways through the resources, as well as providing additional information and imagery (Figures 1 and 2). Links were used in a variety of ways, including acting as home buttons that return the user to the home page, acting as a direct route from one page to another (Figure 3) or as a means of opening pop-up windows, which typically provide additional information and images. Both resources included a number of different areas to explore, including background theory, technical information on how the instruments operate, health and safety information (where appropriate), sample preparation, and calibration procedures. Various points in the resources were supplemented with separately recorded audio narration, which automatically narrated the on-screen text to the user. Additionally, both resources included a capacity for users to analyze virtually a range of samples appropriate to their course. This was achieved by creating a simulated form of data analysis, in which the resource undertakes an "analysis" and provides data extracted from a real data set generated and incorporated within the resource by the creator. Users were able to select a sample to analyze on the basis of a sample identifier and an annotated image or a topographical map of a study area. This aimed to recreate as closely as possible the authentic experience of running the instrument in question, allowing users to "generate" data that could then be applied elsewhere as part of a larger exercise.

Overall, the structure of both resources was designed to adhere to experiential learning,[73−75] as well as scaffolding.[76] An immersive experience was achieved through, for example, creating a "workbench" home page, which relates directly to the actual instrument and contributes to the learner experience. The incorporation of a guided element or "order" in which to move through the resource effectively provides scaffolding,[76] which lessens the potential for learners to become overwhelmed by a daunting quantity and level of learning materials, as well as having the added benefit of overall flexibility—the user can

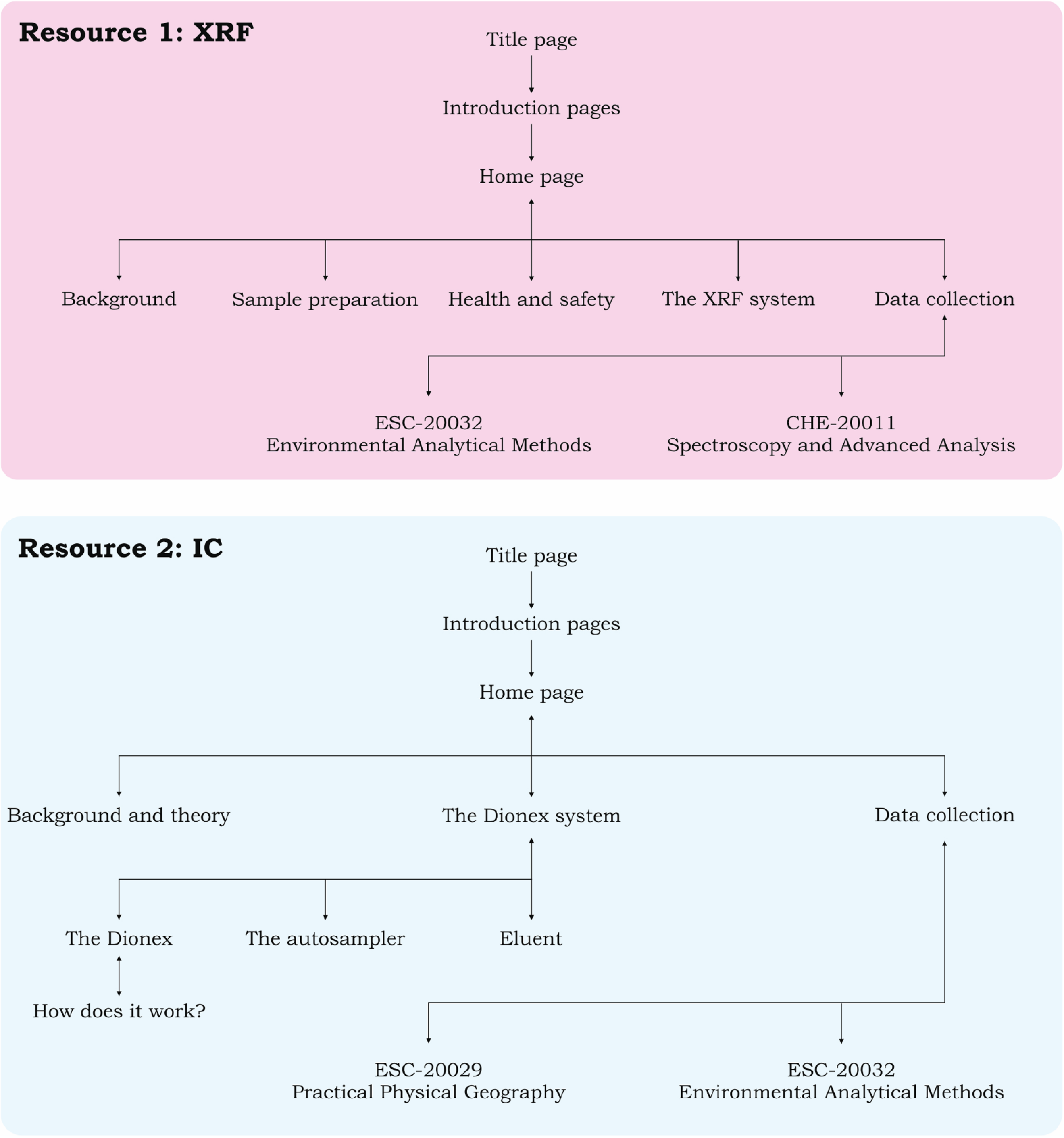

Figure 3. Summarized structure of each Thinglink resource (top/pink, XRF; bottom/blue, IC) showing each section and the various pathways between them. Each section may comprise between 1 and 102 individual pages.

navigate the material at their own pace. On this basis, learners should achieve the "remember" and "understand" levels of Bloom's Revised Taxonomy,[77,78] becoming familiar with underlying principles and background theory associated with the techniques, how the individual components of each instrument operate, and how to operate the instruments to produce data. This final point offers some adherence to the "apply" level of the taxonomy by allowing users to gather data that can then be further treated offline, although there is no reason in principle why data application activities could not be included directly within the resources in the future.

Both resources were made available *via* a weblink to Year 1 to Year 4 undergraduate and postgraduate learners (FHEQ levels 4 to 7+) and teachers derived from Physical Geography-, Environmental Science-, Chemistry-, and Forensic Science-based programs, within the Faculty of Natural Sciences at Keele University, UK. In total, this comprised more than 200 individual students. In each case, due to the impositions of the COVID-19 pandemic, the resources acted as direct replace-

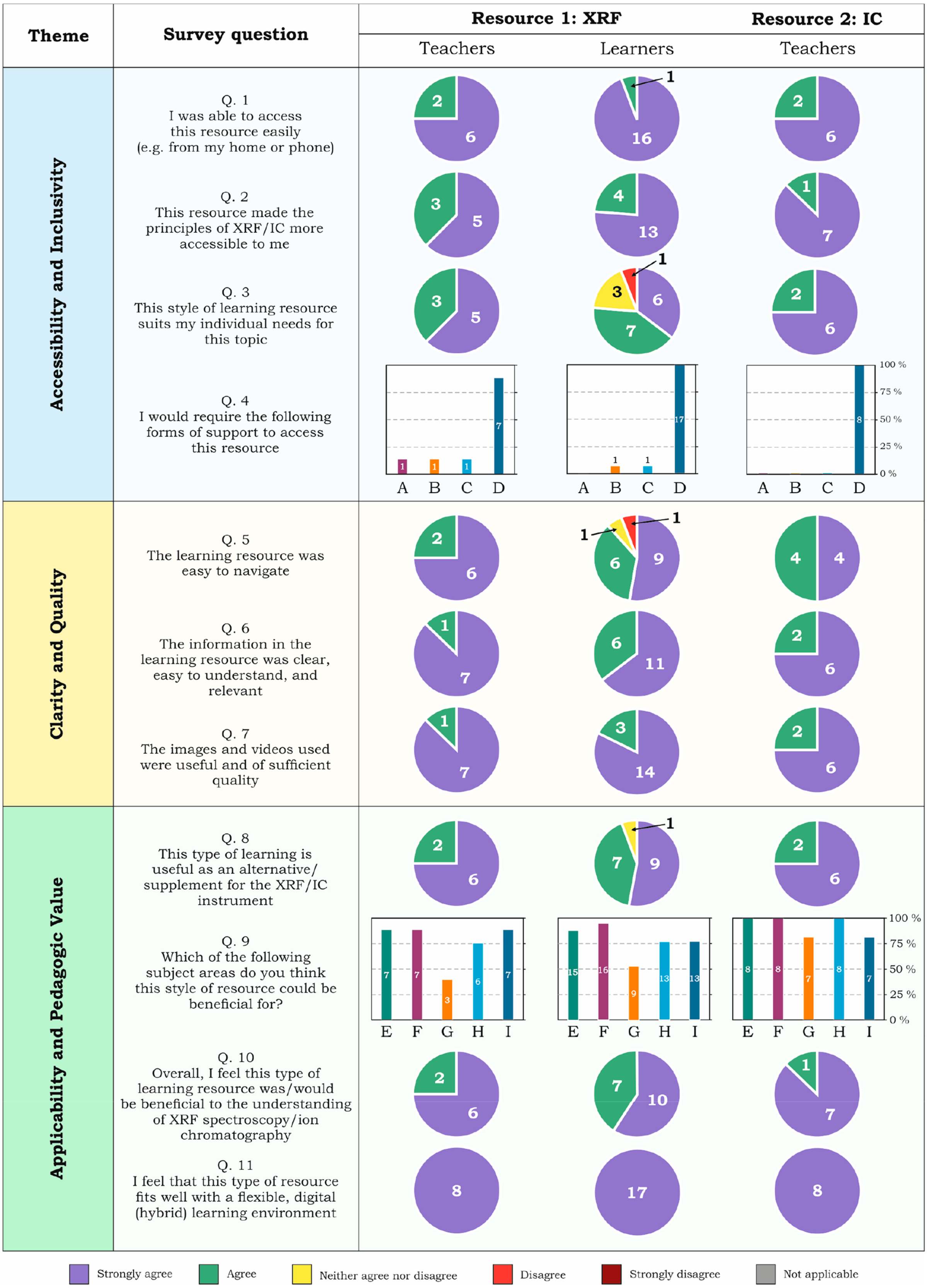

Figure 4. Summarized questionnaire feedback results for Resource 1 XRF and Resource 2 IC. The data are divided to highlight variation between learners and teachers. Histogram data fields: (A) support from another person, (B) specialist software, (C) hardware adaptations, (D) no additional support required, (E) chemistry, (F) forensic science, (G) life science, (H) geology and geography, and (I) environmental science.

ments for actual time ordinarily spent using the respective instrument to generate data that would then be applied elsewhere as part of a larger exercise. The resources were also disseminated to teaching staff derived from the School of Geography, Geology, and the Environment and the School of Chemical and Physical Sciences at Keele University (ranging from demonstrator to professor). Additionally, the resource was made available *via* social media to a range of individuals including educators and students in higher education. Resource 1 (XRF) can be accessed at https://www.thinglink.com/card/1368531711838650369, and Resource 2 (IC) can be accessed at https://www.thinglink.com/card/1360193600519929858.

Collection of User Feedback

This study gathered user feedback from both learners and teachers using two primary methods: (1) electronic questionnaire and (2) semistructured interview. For both resources, access to an anonymous questionnaire hosted in Microsoft Forms was provided alongside access to the resource, disseminated as an open invitation to potential users *via* e-mail and social media. This questionnaire asked users to agree or disagree with a range of statements, using a five-point scale that ranged from strongly agree to strongly disagree and covering the broad themes of accessibility and inclusivity, clarity and quality, and applicability and pedagogic value. These themes were selected as the most fundamental requirements for a new platform of learning, aiming to target the most fundamental aspects of user feedback—if users are unanimously unable to successfully access the resource, then this must be factored in prior to continued development. In addition to these statements, various opportunities were available for users to provide free text comments, thoughts, and suggestions. It was made clear that no personal data would be collected, that all responses would be treated anonymously, and that engagement was on a strictly voluntary basis. To provide information on both learner and teacher perceptions, both parties were invited to provide feedback for both resources. However, it should be noted that no student feedback was received for Resource 2; because of this, this project can only report feedback from academic staff for Resource 2f. All data were analyzed using MS Excel.

One-to-one, semistructured interviews were held with four invited academic staff members to discuss in detail their views on both of the presented learning resources and their potential value. Interviews were undertaken using a general framework of preprepared questions, divided into five key themes (Perception; Clarity and Quality; Accessibility and Inclusivity; Applicability and Pedagogic Value; and Further Development), around which the conversation was loosely constrained. Interview responses were anonymized, collated, and analyzed thematically using a general inductive approach[79]. All data collection processes in this study were given favorable ethical consideration from the relevant Ethics Committee.

■ RESULTS

The data collected in this study are divided into questionnaire feedback (quantitative and open text) and semistructured interview feedback. Quantitative questionnaire feedback is presented in Figure 4 and described below. For the purposes of summarization, and where applicable, responses are divided into positive (strongly agree, agree), neutral (neither agree or disagree), and negative responses (disagree, strongly disagree). Open text questionnaire responses and interview feedback are discussed below based broadly on the respective subthemes of the feedback mechanism (see above) and are given in full in the Supporting Information. In total, the two questionnaires received feedback from 16 teachers and 17 learners. At the time of writing, Resource 1 (XRF) received 956 hits with 462 unique visitors and Resource 2 (IC) received 190 hits with 60 unique visitors. It must be noted that the number of feedback responses is low compared to the overall number of users, and so there may be some bias effects in the responses (e.g., preferential response from more satisfied or more engaged users). Nevertheless, we note the presence of a small amount of negative feedback, which we suggest acts as some validation for the collected data.

Questionnaire Feedback: Resource 1 (XRF)

Quantitative results for student feedback demonstrate overwhelmingly positive responses, with a total of 96% of all feedback being positive (questions 1−3, 5−8, and 10), 3% neutral, and only 1% negative. A single student indicated a requirement for additional support, which they would require to access the learning resource (question 4). In terms of their perceptions of subject areas that would potentially benefit from the application of this style of learning resource (question 9), 88% of the students indicated chemistry and 94% indicated forensic science, 76% indicated geology/geography and environmental science, and 53% indicated life science. All student feedback for question 11 agrees that this style of learning resources fits within the context of a hybrid learning environment.

Staff responses are similarly positive, with 100% of the responses being positive. Unlike the student respondents, one staff member indicated a requirement for support from another person, use of specialist software, and adaptations to their PC to be able to access the resource. All other staff respondents indicated no additional support requirements. Staff responses to question 9 are very similar to student feedback, with 88% of staff indicating potential applicability to chemistry, forensic science, and environmental science, 75% indicating geology/geography, and 38% indicating life sciences. As for the student feedback, all staff respondents agreed that this style of learning resources fits within the context of a hybrid learning environment.

Open text comments are also broadly positive (e.g., "*It's really well done*", "*This was a really useful resource, thank you*", "*I would like to see this used in my future studies*", and "*If this style of resource was incorporated into other geology subjects/practicals, I would definitely use it*"). However, some users highlighted a number of areas for improvement, with staff being more critical overall. Many of these suggestions relate to the user interface (e.g., "*Navigation buttons could be a bit bigger*", and "*···the intended delay between going from page to page is slightly annoying···*") or to the scale and nature of the resource itself (e.g., "*It wasn't as in-depth as I thought it would be*", and "*It's no full replacement for the real thing but it's fine*"). This final comment is noteworthy, as it highlights that the resource should not be regarded as a *replacement* for the real instrument.

Questionnaire Feedback: Resource 2 (IC)

Quantitative results for staff feedback on Resource 2 were entirely positive (questions 1−3, 5−8, and 10). None of the respondents indicated any further support required to access the resource (question 4). The resource was perceived to be highly applicable to a range of subject areas, with all eight respondents indicating applicability to chemistry, forensic science, geology/geography, and environmental science and seven of the eight selecting life sciences. As for Resource 1, all of the feedback agreed that this style of learning resource would be applicable to hybrid learning.

Open text comments are similarly positive to the quantitative results (e.g., "*I love this resource. I already used it for my class and hope to continue doing so*", "*[it's] the ability to work with sample data which is the real master stroke*", and "*[This] is one of the best examples of Thinglink I've ever seen*"). When asked if there were any other analytical instruments that users would like to see "virtualized" in a similar manner, responses included photomicroscopy, scanning electron microscopy, inductively coupled plasma spectroscopy, any field equipment, and, in one case, "*All [school] analytical equipment*". As for Resource 1, there are a number of comments that highlight potential areas for improvement relating primarily to the structure or user interface of the resource. For example, multiple users expressed a desire for more audio narration to narrate the material, and there was a range of comments that indicated minor annoyance with user features such as the timing of hotspot appearance in relation to video completion or the need for more streamlined pathways through the material to enhance navigation. Similarly, there were various comments relating to minor subject-specific inconsistencies or suggested changes (e.g., which analytes were selected and why, and their relation to the column chemistry). Finally, one respondent highlighted that accessibility and inclusivity would be most enhanced by using the resource alongside *in situ* experience with the instrument.

Interview Feedback

One-to-one, semistructured interviews were conducted with consenting participants to establish the following: (1) previous experiences of blended learning; (2) the clarity and quality of both learning resources; (3) the accessibility and inclusivity of the learning resources; (4) the applicability and pedagogic value of the resources, and; (5) thoughts for further development. Summarized responses can be found in the Supporting Information.

All interviewees had prior experience of blended/hybrid learning, including virtual fieldwork and delivery of external workshops, but not necessarily using the Thinglink platform. Not all had used this style of learning resource in their teaching prior to the COVID-19 crisis, but importantly, all four expressed an intention to make greater use of them moving forward, citing the ability for learners and educators alike to revisit material and reinforce learning, as well as the potential for such resources to act as supplementary tools for revision, class preparation, and catch-up for missed classes.

All interviewees expressed satisfaction that the resources were well-structured, easy to navigate, and contained visual and audio elements that were of high enough quality for their needs. Key recurring topics included the value of animations and audio, the potential of a full narration throughout both resources for those with specific difficulties, and the need for proper integration of such materials with tasks for learners to undertake. One interviewee expressed their satisfaction that they had understood the content despite it being beyond their subject area. Another suggested the incorporation of an independent help guide or associated materials that could be disseminated alongside the material and could act as a guide for how to use the resource and potentially help to break up the task(s) for those who struggle to spend lengthy periods working on a computer. In terms of improvements that could be made, suggestions included: (1) incorporation of multiple data sets covering a range of topics within (and beyond) the school/department, (2) development of the user interface to clarify clickable items, and (3) addition of interpretive materials, giving examples of answers to help users make their own interpretations.

Regarding the accessibility and inclusivity of the learning resources, all interviewees expressed the opinion that these resources would make learning more accessible, citing factors such as the promotion of independence, removal of time restrictions for instrument access, tolerance for variability in learning speed, potential reduction of student anxiety, and support for those with physical disabilities, both in the laboratory and during fieldwork. Key identified barriers to this included digital competence (e.g., technophobes or those with limited digital access), physical impairments (e.g., difficulties associated with sitting at a computer screen for prolonged periods of time), technology limitations (e.g., bandwidth), and potential difficulties when trying to encourage learner engagement with asynchronous learning.

Considering the overall applicability and pedagogic value of the resources, opinions were somewhat divided. On the issue of "traditional" teaching (i.e., lectures, practical classes), most interviewees expressed the opinion that traditional teaching was not the most efficient and is often employed purely out of tradition or because it is easy for the teacher. Nevertheless, one response highlighted the social benefits of a synchronous lecture with discussion-based elements compared with a purely asynchronous class. Despite this, the general opinion was that traditional approaches alone are insufficient, and all four interviewees felt that application of learning resources such as those employed by this study had the potential to diversify physical and chemical science education, which they recognize as a good thing to do. However, the time and effort required to create such materials were acknowledged as a major caveat. It was suggested that the time required could only be justified if the materials were prioritized and integrated with multiple modules to maximize efficiency. In terms of broader applicability, it was widely reported that there were no real boundaries in terms of discipline or academic level, with laboratory and field-based teaching across the physical sciences being equally capable of benefiting from such learning materials.

Regarding further development of the learning resources and the features that users might like to see in the future, the recurring theme was expanding this approach to as many other instruments as possible, as well as potential high-end instruments that are not available at Keele University due to their costs of acquisition and upkeep. It was also suggested that a broad, virtual laboratory with multiple virtual resources integrated into it would be beneficial and that more material could be included on navigation within the resources to maximize engagement. Finally, all four interviewees expressed their openness to using these resources and materials in their own teaching in the future.

■ DISCUSSION

The overall aim of this study has been to investigate the potential of using Thinglink-based virtual learning environments as complementary educational tools to mitigate or reduce barriers to laboratory-based learning. The feedback received, although primarily positive in nature, has highlighted a number of key strengths and weaknesses to this approach, as well as some key points that must be considered during the planning, creation, and implementation of Thinglink-based learning resources.

Limitations of the Study and the Platform

The results of this study are highly positive regarding the applicability of Thinglink-based virtual laboratory resources. However, there are some clear limitations to the scope of the study that must be highlighted before considering how to move forward. First, the overall size of this study is limited in the number of respondents and reach. In total, the modest feedback of this study is derived from 17 students and 20 staff members. As such, the diversity of experiences, backgrounds, and contexts among the respondents may not be very large and will clearly not be fully representative of the breadth of opinions, needs, and circumstances that exist within the wider world of higher education. Similarly, the number of respondents is significantly smaller than the number of users of the resources, which inevitably introduces the risk of unavoidable bias in the results, introduced through the potentially preferential response of certain participants (e.g., those who were most engaged or most satisfied with the resources).

It must also be recognized that this study addresses only the perception of the resources (i.e., the contribution to student experience and satisfaction, and the enhancement of accessibility and inclusivity). We do not attempt to measure or to address directly the effect the resources have on academic performance. It is, therefore, important to avoid overinterpreting the results of this study or extending them beyond their scope. This study reflects a promising proof-of-concept that will undoubtedly require further research to demonstrate its continued applicability to a larger, more diverse cohort of needs and preferences, as well as thorough investigation into the potential power of these resources to impact (positively or negatively) the academic performance of learners.

Despite the generally positive tone of the feedback received, there remain some negative key points and challenges associated with the platform and the developed learning resources that must be considered. The most highly recognized and most significant negative point associated with Thinglink-based learning resources (and other virtual lab resources) is the time required to create them in the first instance and then maintain and update them if required.[63,64] This is recognized in the feedback of this study and in many other studies surrounding virtual laboratories.[80] To some extent this is unavoidable; however, the time investment required can, in some cases, be justified *via* thorough planning. If individual resource development includes a significant planning stage in which factors such as the longevity, transferability, and overall depth are considered in detail, then it seems possible to create an efficient resource that achieves its goals for the maximum possible lifespan, thereby helping to justify the costs.

In addition to time requirements, it was suggested in the feedback that these resources would not perform as well if used in a standalone fashion and that even traditional lectures include a social element that is not provided by this form of learning. This represents a significant challenge for virtual laboratory resources such as those presented here, where the collaborative or social element of learning is either absent or more difficult to achieve.[62] Although direct communication *via* Thinglink is not currently possible, this could be to some extent accounted for if suitable provision for student communication and collaboration is made. However, this is linked more to the creativity of the resource and curriculum designers to implement additional and diverse platforms or mechanisms within their learning activities.

It was also raised that digital competence, technophobia, and digital access are also potential challenges for the successful implementation of Thinglink-based learning resources. For example, learners who find the use of digital materials difficult, or who, for any reason, struggle with lengthy periods of working with a PC, will inevitably face barriers to learning.[81,82] Students with physical impairments may, for example, find it difficult to sit at a computer for prolonged periods of time or those with visual impairments may have difficulty using a screen for lengthy periods of time. This represents a real challenge to any learning resource of this nature and highlights the importance of adequate instruction. This could be achieved through direct instruction prior to use or the provision of guide materials and help sheets, which could be integrated directly with the resource itself. The provision of a learning material such as those of this study, without any support, will inevitably exacerbate existing disparities in technical capabilities among the learner population. Similarly, its use should not be so substantial as to create fatigue. As others have also pointed out, however, the virtual practical may still last less long than a physical one, which is appreciated by students.[51] Resource designers should ensure that the materials are applied in a supplementary fashion and not relied upon as the primary means of education.

A further challenge that cannot be ignored is learner engagement (i.e., the student's cognitive and emotional energy to accomplish a learning task[83,84]). If learners are unable to engage with the learning resources, the time taken to create them will be wasted and the negative academic outcomes for the learners could be considerable.[85−88] The factors that influence learner engagement are complex, particularly in a blended learning environment where their various roles are not well-understood, and a thorough analysis of them is beyond the scope of this study.[84] However, one feature that was raised in the feedback of this study that could impact learner engagement is interactivity,[89] a feature known to have potentially positive,[85,90] mixed,[91] and negative effects[92]. The primary interactivity of the resources presented here comes from the users ability (and requirement) to navigate through the resource, having the freedom to choose their own path, which was raised as a positive point in the feedback. However, it was also suggested that this could be enhanced further through the incorporation of quiz elements, which allow users to test themselves on the content (a function that has recently become available on Thinglink). This style of e-learning resource would also be readily enhanced by gamification pedagogies, integrating game-based mechanics such as problem-solving and a reward system.[93]

Overall, there are a number of challenges to the implementation of Thinglink-based virtual laboratory resources. However, we suggest that the majority of these challenges are intrinsic to the concept of a virtual laboratory rather than being specific to the method employed here. To ensure success, most of the responsibility lies with the designer(s) to plan the resource, maximize its efficiency, and cater to the needs of a diverse student cohort. They should also implement it alongside other materials and teaching strategies as part of a hybridized learning approach, maximizing student engagement through features such as interactive elements and gamification and moving beyond simple transmissive learning.

Study Implications and Moving Forward

This study highlights a significant positive response from both teachers and learners to the creation and application of Thinglink-based virtual learning resources. The disseminated resources were perceived as being of high quality, easy to reuse over multiple academic years, and readily shared and disseminated as examples of good practice. Users commented positively on the freedom that the resources gave them over the time and manner of their learning and highlighted their potential power to enhance accessibility and inclusivity, two themes that are recognized as vital for technology-based learning[94] and are protected by the Equality Act in the U.K.[95] The resources presented here offer a positive resolution to a number of inclusivity challenges, such as access to instrumentation that may not always be available and also allows users to undertake learning at their own pace, in an environment of their own choosing, and without the pressures associated with the laboratory. For example, use of these resources as a preparatory or training tool has the potential to reduce anxiety in some learners by allowing them to take their first learning steps within a given area prior to any face-to-face teaching, giving them the opportunity to make mistakes privately (e.g., fear or failure[96]), and in a familiar environment.[60] It also has the potential to enhance the efficiency of face-to-face teaching by giving learners the chance to learn the basics of, for example, instrument operation, before they operate the real thing, potentially overcoming some of the anxiety that can be associated with laboratory-based learning.[97,61] Similarly, the ability to incorporate audio narration directly within the Thinglink resource may offer some support for those with additional needs (e.g., visual impairment), as well as scope for interaction with a pedagogical agent.[98,99]

The applicability of Thinglink-based resources to a range of disciplines and levels was also recognized, from undergraduate to postdoctoral education, in almost all of the major sciences. It was suggested that this style of resource could easily be rolled out for many or all of the analytical instruments available and could even include instruments that are not present in, or available to, specific institutions and that cannot be used for teaching due to costs of acquisition and blended/hybridized learning and maintenance. The majority of teachers who participated in the study identified the need for this style of resource, particularly having been obliged to apply similar materials during the COVID-19 pandemic. This form of resource was also identified as having potential for other uses, including field-teaching.

Overall, one of the greatest strengths of the Thinglink platform is its simplicity and user-friendliness, allowing users to easily create and disseminate immersive, interactive learning materials with very little training time. This permits the creation of bespoke digital learning resources that adhere to modern principles of curriculum design and, on an institutional level, educational vision and strategy. For example, the resources presented in this study were informed by the Keele Social Curriculum and Curriculum Design Framework[100] (Figure 5). This framework sets out key principles for innovative program design, within the broad themes of Digital Education, Sustainability, and Health and Wellbeing, to which the Thinglink resources of this study potentially contribute. For example, as described above, the general features of the relatively specific Thinglink resources presented here synergize well with the Technology-Enhanced Learning (e.g., application of asynchronous digital resources and media to support learning) and Inclusive Learning (enhanced flexibility and learner control) components of the framework. Similarly, the ability for learners to have additional access to specific instrumentation, albeit in a virtualized format, offers some scope to contribute to the Employability and Civic Engagement component, permitting enhanced opportunity for the development of subject-specific skills that are dependent upon instrument or laboratory access, as well as potential application to outreach activities. The ability to repeat the experiment whenever learners wanted also reinforced learning as others have evidenced.[19] Finally, the ability to allow learners to access a virtual form of an analytical instrument and laboratory space opens a number of interesting possibilities for authentic assessment. For example, assessment activities that would be inhibited by high student to instrument ratios could be virtualized, allowing a remote form of instrument usage and assessment in which any number of learners can simultaneously access the instrumentation.

Figure 5. Keele Curriculum Design Framework.

The results of this study have demonstrated that Thinglink is a powerful but imperfect tool for the creation of virtual learning resources relating to laboratories and associated instrumentation. This is not the first attempt to create a virtual laboratory, but its key strength is the user-friendly platform, which allows for considerable flexibility in design. Moving forward, user feedback has highlighted the following areas for potential improvement:

- Provision of additional supporting materials to assist in use of the Thinglink resource (e.g., help sheets and guides)
- Inclusion of more video-based materials and interactive elements such as "test-yourself" quizzes
- Overall refinement of resource transitions, hotspot locations, and specific investigation of smartphone-based application
- Addition of broader, nonmodule-specific academic content to allow for broader analysis of different materials, highlighting the instrument and method, rather than a specific learning task
- Development of a narrator *via* real voice recordings rather than complete reliance on the in-built text-to-speech function
- Potential development of high-end virtual instruments that are not currently available at all due to their substantial costs of acquisition (e.g., electron microprobe)

- Review of navigation tools and overall structure to facilitate rapid and efficient movement within the resources
- Incorporation of individual resources into a larger virtual lab, with 360° images that allow for “movement” through the lab and access to different instruments and techniques

Overall, the key recommendations of this study are to ensure that Thinglink-based virtual learning resources are planned from the outset to maximize their efficiency and lifespan and are applied as a supplementary learning material, in conjunction with more traditional, face-to-face laboratory teaching. Their application has the potential to contribute to the enhancement of accessibility in laboratory-based education and in chemistry and other fields. It is however worth noting that, although the provision of such learning resources may enhance accessibility for users who have difficulty accessing *in situ* learning, learners who experience difficulty accessing digital and online resources (e.g., those with learning difficulties or those from low income backgrounds, which inhibit access to digital resources) should also be considered.[101] One means of ensuring that learners with disabilities affecting their access to digital resources are not placed at a disadvantage might be implementation of “reasonable adjustments” by institutions.[95]

The rationale behind this study was not to replace actual hands-on, practical laboratory experience, which the authors, respondents, and literature studies each recognize as being invaluable to development of key skills. Furthermore, the resource users who participated in this study also expressed similar thoughts regarding the real value of such resources being their application in a supplementary capacity. As such, we recommend that the main driving force behind the development and implementation of Thinglink-based virtual learning resources and simulations should be the aim of enhancing accessibility and inclusivity through their provision in a supplementary rather than replacive fashion.

CONCLUSIONS

This pilot study of generating high quality, online laboratory equipment simulations has demonstrated the applicability of the Thinglink platform as a means of enhancing student engagement and experience. The interventions presented here included virtual laboratory resources that could be accessed at all times, repeatedly interrogated to improve and reinforce student learning, and used for a variety of purposes from pre-equipment orientation to high level understanding and extraction of data sets to be used for further teaching. The most prominent drawbacks raised by the feedback were the time required to produce and develop such resources and potential difficulties relating to individual users who struggle with computer use (e.g., individuals with disabilities or who are technophobic). Study limitations include the number (and academic level) of student participants in the project and the limited scope of feedback derived primarily from two different degree programs. Moving forward, further research is suggested to progress this proof of concept work, by developing the online learning tool further and providing more online resources, perhaps including other analytical instruments, even those that are not available due to high purchase and running costs. This could also widen the student participant data sets to undergraduates throughout the Faculty of Natural Sciences and beyond. We also highlight the importance of further evaluation by quantifying the effects of these interventions on subsequent academic performance postintervention.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c01067.

Tabulated questionnaire responses to open text-based questions (PDF, DOCX)

Tabulated summarized responses to the face-to-face interviews (PDF, DOCX)

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Notes

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