The pedagogical benefits and pitfalls of virtual tools for teaching and learning laboratory practices in the Biological Sciences

The Higher Education Academy

STEM

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November 2014

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Executive summary

Over the recent years, the number of traditional hands-on laboratory sessions incorporated within degree programmes in the Biological Sciences has been declining; to be replaced, in some instances by virtual laboratories and tools. This project critically reviewed the pedagogical benefits and pitfalls of this increased use of virtual laboratory tools across the Biological Sciences, both within the UK and internationally.

Despite a substantial number of virtual laboratory tools being deposited in open educational resource (OER) repositories, there were limited reports of these or their use in the published literature. Discovered tools included simulations of cellular or organ function, virtual microscopy, interactive "real life" scenarios or problem-based learning exercises, virtual reality or Second Life scientific worlds and human patient simulators. The use of these spanned the Biological Sciences.

Virtual laboratory tools were equally effective as traditional laboratories in increasing student knowledge and understanding, when evaluated by student performance in examinations. They facilitate active, enquiry-based learning rather than the passive, protocol driven learning normally found in traditional laboratories, are low cost and enable students to learn in their own time and pace. Their use also overcomes health and safety constraints and ethical issues. However, they do not provide hands-on experience of individual techniques or training in the use of individual items of equipment, health and safety or promote awareness of ethical issues. The data generated by these tools lacks biological variation and is constrained by the assumptions of the underlying model; therefore, students do not gain experience of analysing and interpreting incorrect or uncharacteristic data.

However, there are substantial educational benefits to be realised when high-quality virtual laboratory tools are fully integrated alongside traditional laboratory sessions within curricula, each complementing, reinforcing and enhancing the learning from the other. Therefore, the use of virtual laboratory tools within UK undergraduate degree programmes in the Biological Sciences should be substantially increased, with these not replacing but being utilised alongside, and fully integrated with, traditional laboratory sessions. Discipline specialists, learning technologists, students and educationalists should work in partnership to develop new high-quality virtual tools, making full use of emerging technologies and tools to create exceptional enquiry-based learning experiences for students. These tools, technologies and impact of these interventions should be evaluated and shared with the community.

1. Introduction and aims

The opportunity for students to engage in practical work is an essential component of degree programmes in the Biological Sciences. Indeed, the Quality Assurance Agency for Higher Education (QAA) Biosciences Benchmark Statement notes that "the Biosciences are essentially practical and experimental subjects", advising that "appropriate opportunities to participate in collecting data by undertaking experiments and practical investigation … are integral to any scheme of study in this area" (QAA 2007). Practical work, whether it be in the laboratory, field or "in-silico":

- re-enforces knowledge and understanding of materials and concepts introduced in other teaching sessions;
- provides the opportunity for students to develop competence in experimental skills appropriate to their discipline;
- increases knowledge and understanding of the principles of experimental design, data collection, analysis and interpretation, and report writing, with opportunities to engage in these activities;
- provides awareness of biological variation and appropriate methods to deal with this variation, including data handling and statistics;
- enables students to develop key graduate skills and attributes including application of knowledge, critical analysis, communication skills, numeracy, resilience, problem solving, self-reliance and team-working.

However, increases in student numbers, the high cost of traditional wet laboratory practicals coupled with decreased resource has led to a reduction in the practical content of undergraduate degree programmes in the Biological Sciences. Practical sessions have either been removed from curricula or replaced with computer-based alternatives (ABPI and Biosciences Federation 2007). The aim of this research project was to review and critically appraise the use of virtual versus traditional laboratory tools within degree programmes in the Biological Sciences, both within the UK and internationally. Specifically, to:

- provide an overview and critical appraisal of the current use of virtual laboratory tools across higher education institutions (HEIs) in the Biological Sciences, both within the UK and internationally;
- identify instances of best practice with regard to (a) the effective use of virtual laboratory tools in isolation and (b) the effective use of virtual tools jointly with traditional hands-on laboratory learning;
- identify how virtual laboratory tools can complement and supplement traditional hands-on laboratory learning;
- provide recommendations on the appropriate use of virtual laboratory tools to improve learning outcomes and the experience of students in the biological sciences within UK HEIs.

2. Research methodology

A systematic review and critical appraisal of the published literature was undertaken. The principal publications databases for the Biological Sciences (BIOSIS, CAB, ERIC, Medline, OVID, ProQuest, PubMed, Scopus, Web of Science, Web of Knowledge) were searched (9 March 2014 to 14 March 2014) for publications which described the use of virtual laboratories, computer simulations, e-learning or blended learning in laboratory environments within undergraduate degree programmes in the Biological Sciences, both within the UK and overseas. In addition, specific searches, using the above search criteria, were also undertaken of all past issues of the *Journal of Biological Education* (Society of Biology) and *Bioscience Education* (Higher Education Academy), and of the publically available conference proceedings of the Biochemical Society, the British Pharmacological Society, the Federation of American Societies for Experimental Biology (FASEB) , the Physiological Society, the Society for Experimental Biology and the Society for General Microbiology.

One hundred and fifty-four full publications or conference proceedings were discovered which, from their titles and abstracts, appeared to meet the search criteria. These were evaluated by reading the full publication (or abstract for conference proceedings), excluding those (n = 29) either that did not meet the inclusion criteria (virtual laboratory, e-learning in laboratory environments, biological sciences, etc.) or where the full paper was not available at the University of Leeds and the abstract contained insufficient detail to evaluate it. From the remaining papers and proceedings, details of the intervention, assessments, student and staff perspectives and comparisons with other learning methods or tools were extracted. This information was recorded and critically analysed.

3. Use of virtual laboratory tools within the UK and internationally

Twenty-nine full publications or conference proceedings were discovered which describe the use of virtual laboratory tools within UK Biological Sciences degree programmes. The remaining 96 describe interventions within North American (67%), Australasian (14%), European (12%), Central/South American (4%) or Indian (3%) programmes.

The usage of virtual laboratory tools was not restricted to a limited number of disciplines but spanned the Biological Sciences from molecular biology to ecology. These tools included computer simulations of single cells, cellular processes or organs (Av-Ron *et al*. 2006; Davis and Gore 2001), virtual microscopy (Bonser *et al*. 2013), virtual dissections (Predavec 2001), human patient simulators (Cesari *et al.* 2006), interactive scenarios to virtual reality and Second Life science environments (Clarke 2009; Flint and Stewart 2010; Stafford *et al*. 2010).

The very limited number of publications discovered does not reflect the true extent of the usage of virtual laboratory tools across the sector, both within the UK and internationally. For example, LifeSciTRC (http://www.lifescitrc.org), the American Physiological Society's repository of open educational resources (OERs), contains 676 apps, simulations, software, online tools, laboratory exercises and data sets suitable for use in undergraduate physiology degree programmes. ERIN (http://erin.sfn.org), the US Society for Neuroscience's OER repository, contains 58 similar resources whilst Jorum (http://www.jorum.ac.uk), the UK's OER repository, has 9. Many other resources will have been developed by colleagues for their own use, with these not being shared or disseminated beyond their own Institutions.

Given the limited number of publications, both from the UK and overseas, describing the use of virtual laboratory tools within Biological Sciences curricula, the remainder of this report will not distinguish between the two but will provide a review and critical appraisal of their global use.

4. Use of virtual laboratory tools as a replacement for traditional laboratory sessions

Increasing student knowledge & understanding

The integration of traditional wet laboratory sessions into courses and modules reinforces concepts introduced in other teaching sessions and increases student knowledge and understanding of their discipline. Virtual laboratories have a similar effect. Student performance in examinations or other assessments and therefore, by implication, their knowledge and understanding, is improved in comparisons either of assessment scores, pre versus post, a virtual laboratory session (Crisp 2012; Cunningham *et al.* 2006; Karamanos *et al*. 2012; Meir *et al*. 2005), or in lecture courses with the inclusion of virtual laboratory sessions compared to those without (Russell *et al*. 2004; Wolfe 2009). The educational benefits of virtual laboratories are realised regardless of format of the intervention or discipline.

When direct comparisons are made between the knowledge and understanding gained from traditional versus virtual laboratory sessions, there is no difference in student examination performance, both formats are equally effective in enhancing student learning irrespective of discipline (Dobson 2009; Gibbons *et al*. 2004; Sancho *et al*. 2006). However, it is questionable whether examination performance alone provides a suitable measure by which to compare the effectiveness of virtual versus traditional laboratory tools. Increasing student knowledge and understanding of academic content is just one of many learning outcomes for laboratory sessions. There are many others – for example, knowledge and understanding of the principles of experimental design and the ability to apply these; data handling, analysis and interpretation – and, therefore, other comparators or means of evaluation should be utilised. To date, there are no reports of such evaluations in the published literature.

There are specific instances where virtual laboratories provide a better learning experience than traditional laboratories. For example, in botany, the use of virtual microscopy slides enables students to view high quality digital images rather than the low quality slides they would have produced themselves in traditional laboratories; the increased quality of resources and student engagement in the session reflected in increased examination performance (Bonser *et al*. 2013).

Whilst the above provides evidence that virtual and traditional laboratories are equally effective in increasing student knowledge and understanding of the academic content of their discipline, they cannot fully replace traditional laboratories. Virtual laboratories do not provide students with opportunities to develop key practical or technical skills for example, the setting up experimental preparations or the use of specific items of equipment. They do not provide students with exposure to, and experience of, analysis of uncharacteristic or incorrect data. They always work, creating the false impression that this is always the case in "real" scientific research. Therefore, if development of these skills forms part of the learning outcomes for the course, these cannot be achieved using virtual laboratory tools.

Student perceptions and engagement

Students overwhelmingly recognise the educational benefits of virtual laboratories (Bean *et al*. 2011; Dobson 2009). They facilitated their learning (Grisham 2009), made them think (Cunningham *et al*. 2006) and increased their knowledge and understanding of course content (Kinnison *et al*. 2009; Sancho *et al*. 2006). Student acceptance of virtual laboratories increased if resources were seen as relevant, interesting, of a high quality and easy to use (Bonser *et al*. 2013; Dewhurst *et al*. 1994; Russell *et al*. 2004).

Appropriately designed and created, virtual laboratories can increase student engagement. They enable students to participate in enquiry-based learning, to formulate and test hypotheses (Bartocci *et al*. 2011), to focus on data collection, analysis and interpretation, rather than acquisition of technical skills or having to overcome the problems associated with live experiments (Grisham 2009; Macaulay *et al*. 2009). Students particularly welcome the fact that they are guaranteed results, experiments are repeatable, they can work at their own pace and make mistakes (West and Veenstra 2012). Virtual laboratories also promote the opportunity for collaborative and peer-supported learning (Bonsor *et al.* 2013).

However, there are few direct comparisons of student preferences for virtual or traditional laboratories. Student opinion is equally divided. They prefer virtual laboratories where the material or content is more suited to computer-based delivery, for example: bio-informatics (Weismann 2010), cellular neurophysiology (Grisham 2009), or genomic case-studies in simulated (virtual reality) environments (Clarke 2009). Likewise, virtual microscopy is preferred to light microscopy because digital images are much higher quality than traditional glass slides, and therefore facilitate greater learning (Bonser *et al.* 2013; Macaulay *et al.* 2009). Surprisingly, over two-thirds of students preferred traditional wet laboratories for studies involving humans, animals or animal tissues (Dobson 2009; Franklin *et al.* 2002; West and Veenstra 2012). They view traditional laboratories as being more realistic; an opportunity to develop technical skills and gain "hands-on experience" (West and Veenstra 2012), overall providing a better learning experience and enabling them to see the bigger picture or "how things fit together" (Franklin *et al.* 2002). If asked whether either virtual or traditional laboratories should be discontinued, students saw a place for both within the curriculum, recommending that they should be used in parallel (Dewhurst *et al.* 1994; Macaulay *et al.* 2009).

Many resources discovered and reviewed in this research project were over ten years old; they used what are now redundant technologies or contained limited interactivity (Booth 1986; Booth *et al.* 1988; Dewhurst *et al.* 1994; Franklin *et al.* 2002; Samsel *et al.* 1994). Current students are the "Digital Generation"; advanced technologies play a bit part in their lives, they are used to high quality digital resources and games. Thus, it is highly likely that these student reviews would be markedly less favourable if these evaluations were to be repeated now, unless the resources had undergone significant re-design and re-formatting to meet current student expectations.

Constraints and limitations of virtual laboratory tools

Virtual laboratories tools are not perfect; they have intrinsic constraints and limitations. Computer simulations of cells, organs or processes, and therefore student learning, is limited by the underlying assumptions and characteristics of the model. The accuracy of data outputted from simulations and models may be further decreased if used outside of their intended or design specification. For example, human patient simulators are designed to provide clinical training, the model requires modification of the underlying assumptions if used to demonstrate physiological function in extreme environments (Cesari *et al.* 2006; Lloyd *et al.* 2006). Biological variation is invariably absent and users cannot collect, and therefore learn, from poor, unusual, or uncharacteristic data (Dobson 2009). Individual software authoring tools may possess intrinsic technical limitations which restrict the design and functionality of virtual laboratory tools and therefore student learning. For example, when using the interactive scenario authoring tool, SBL Interactive, it is hard to create sophisticated branching within a scenario (e.g. provision of an inappropriate or confusing result when students select the wrong experiment; the ability to send them back to the place where they had made the wrong decision rather than the beginning of the scenario) (Breakey *et al.* 2008). Virtual laboratory tools cannot be used to teach most generic laboratory skills, how to use specific items of equipment or to promote awareness of ethical issues or health and safety requiring these to be taught in traditional laboratories elsewhere in the course (Bonser *et al.* 2013; Flint and Stewart 2010).

For students used to timetabled, passive, protocol-driven traditional laboratories, virtual laboratory tools are an alien way of learning. They have to learn time management, collaborative learning, peer-assisted learning, and to participate in online discussion forums, to make decisions and design experiments or courses of action based on information obtained, and to participate in active, enquiry-based learning. In designing virtual laboratory tools, to fully realise the benefits of these in promoting active, enquiry-based learning, educators should incorporate tools and processes to encourage and facilitate the above and refrain from providing protocols or excessive guidance (Weissman 2010).

Overcoming constraints or limitations of traditional laboratories

Disciplines where activities or interventions are predominantly web or computer focused, such as bioinformatics (Weissman 2010), proteomics (Ray *et al*. 2012) or studies of enzyme kinetics (Amorim *et al*. 1999; Edginton and Holbrook 2010), are better delivered as virtual laboratories. Likewise, computer simulations can provide opportunities for students to perform experimental manipulations that would be inaccessible in real-life (e.g. investigations of the interplay between the biophysical and dynamic properties of neurones and their synaptic connectivity, Av-Ron *et al*. 2006), are technically extremely demanding (e.g. voltage clamp experiments of cardiac cells, Le Guennec *et al*. 2002) or to manipulate individual variables in a complex system (Davis and Gore 2001). The preparation and maintenance of anaesthetised animal preparations requires considerable skill and care, a significant stressor and distraction for students. Replacement of these animal preparations with simulations removes this anxiety, enabling students to focus on the primary learning outcomes of the session. Other disciplines are constrained by time. Studies of genetic inheritance, genetic mutations or ecology typically take weeks or months (Breakey *et al*. 2008; Carvajal-Rodriguez 2012; Latham and Scully 2008; Stafford *et al*. 2010). They cannot easily be incorporated into a standard three-hour traditional laboratory session and, therefore, without virtual laboratory tools, they may be omitted from undergraduate curricula.

Virtual laboratory exercises and tools enable students to learn at their own pace, re-visit exercises, and at a time and location to suit themselves (Flint and Stewart 2012; Ray et al. 2012), an increasingly important consideration in UK higher education (HE) with more students undertaking part-time employment to support their studies or for distance learners. They always work and the data is consistent, student learning is not compromised by incorrect data. Experiments are far shorter, students can undertake more experiments in the time available, increasing their learning. The volume of data is such, that students can be trained in, and undertake, meaningful statistical analysis (Latham and Scully 2008).

Virtual laboratories and tools also provide significant long-term cost savings. Whilst the initial development or purchase costs may be large, once developed, with the exception of, for example, human patient simulators, the majority do not require the ongoing purchase of consumables, the provision of physical space, laboratory equipment or support staff time, a significant benefit for institutions that do not have the facilities or resources to provide all the traditional wet laboratories they would like. Further, once an initial resource is created, if the underlying framework is generic, additional resources can be developed using this template at minimal cost (Flint and Stewart 2010).

Overcoming ethical issues and/or legal constraints

Virtual laboratories and tools have the potential to overcome the ethical issues and legal constraints surrounding the use of human participants or animals and animal tissues in undergraduate education.

Use of animals and animal tissues

Over the last 25 years, there has been a substantial global decline in the use of live animals, cadaveric dissection or isolated tissue studies in student education (Leggett 2005; Ra'anan 2005). The majority of these sessions have been removed from the curriculum and not replaced, or replaced with non animal/animal tissue alternatives (ABPI and Biosciences Federation 2007). However, this continued use of animals and animal tissues in education remains controversial. If asked, 8-15% of students object to participating in laboratory sessions in which they are required to use animals (including cadaveric dissections) or animal tissues (Dowie and Meadows 1995; Franklin *et al*. 2002) and would opt for an alternative if so offered (Franklin *et al*. 2002). If the learning outcomes of the session include, for example, the development of surgical skills or knowledge and understanding of the integration of multiple physiological systems in-vivo, these cannot currently be addressed with non-animal alternatives. However, if these do not form part of the learning outcomes, academically equivalent virtual tools, for example, dissection simulations (Predavec 2001), latex models (Dowie and Meadows 1995), non-mammalian organisms and tissues (Santoriello and Zon 2012) should also be offered as an alternative to students to address their ethical concerns.

The use of live animals in student education is a "permissible purpose" under the Animal (Scientific Procedures) Act, 1986 (Home Office 2013), the UK legislation governing the use of animals in scientific and medical research. However, there are substantial restrictions on the nature of the studies that can be undertaken and a requirement to obtain the necessary licences under the Act. There are also significant costs involved. As a consequence, few students are provided with this education during their undergraduate studies. There are no legislative restrictions on the use of animal cadavers or tissues.

Use of student participants

Similarly, many human physiology and pharmacology laboratories have also been removed from undergraduate curricula due to an increased awareness of health and safety issues and ethical concerns, to be replaced by safer, or more ethically acceptable, alternatives which still involve student participants.

One alternative to sessions involving student participants is to use human simulators; their use bypassing the need to obtain independent ethical review of the sessions and to gain informed consent from the participating students. Simulators also enable students to undertake experimental manipulations or investigations that were not previously possible, for example, extreme physiological environments or administration of high doses or multiple pharmacological agents (Cesari *et al*. 2006; Hughes *et al*. 2008; Hyatt and Hurst 2010). However, these simulators are designed for the provision of clinical training and, whilst they are excellent in demonstrating physiological principles, the underlying computer models have to be refined to provide a more robust simulation of experimentally derived data or extreme environments (Hyatt and Hurst 2010; Lloyd *et al*. 2006). There are also significant costs associated with their purchase and maintenance and would, therefore, be beyond the means of most departments unless linked to clinical training programmes.

Enhanced learning experience

By enabling experimental manipulations (that may take weeks in real-life) to occur at the click of a mouse button, virtual laboratories or scenarios not only allow students to undertake these studies but, more importantly, to have an enhanced learning experience. The majority of traditional laboratory sessions for Biological Sciences undergraduates in the UK are two to three hour, protocol driven, passive sessions. With the exception of a few institutions – that have introduced innovative, extended practical modules or mini-projects at levels five and six (Bevitt and Wilson 2009; May 2014) that require students to design and conduct experiments over a number of weeks to address a scientific question – the majority of students do not receive training in experimental design prior to their final year research project. Virtual laboratories provide the opportunity for students to be provided with an active, enquiry-based learning experience; to engage in experimental design, conduct experiments, gather, analyse and interpret meaningful data; receive instant online feedback before deciding, and then undertaking, the next experimental manipulation (Breakey *et al*. 2008; Cunningham *et al*. 2006; Latham and Scully 2008). There is also the potential to include the cost of individual interventions into their decision-making processes (Flint and Stewart 2010). By removing the need for students to become proficient in technical or experimental skills before they can acquire meaningful scientific data, virtual laboratory tools enable students to focus on the underlying scientific concepts. Online discussion forums can be utilised to promote collaborative learning and peer support, further enhancing their educational experience (Weismann 2010).

In creating virtual laboratory tools, educators should not just digitise existing wet laboratories. They need not be just demonstrations, simulations, or cook-book exercises. Rather, they should consider the intended learning outcomes, explore the full range and potential of digital tools (e.g. discussion forums, online assessment with instant feedback, peer-supported learning, real-life scenarios), integrating as many as possible to create a high quality, active, enquiry-based learning experience for students which is fully integrated into both the course and other e-learning environments.

5. Best practice in the use of virtual laboratory tools in isolation or jointly with traditional laboratories

Use of virtual laboratory tools in isolation

Virtual laboratory tools can be more effective than traditional laboratories in providing student learning in instances where the experimental technique would not be possible or the manipulation inaccessible in a traditional laboratory environment. Likewise, web-centric or computer-centric learning is best delivered using virtual laboratory tools. Virtual laboratories can be used to overcome health and safety concerns, time or location constraints, or ethical and legislative issues. They are particularly effective in moving beyond a typical, protocol-driven traditional laboratory to provide active, enquiry-based learning rather than passive learning, an education in the formulation and testing of hypothesis, and training in experimental design, overall an experience much closer to real research.

Examples of best practice of the above are provided below:

Cellular Neurophysiology (Molitor *et al*. 2003) is a computer simulation which enables students to investigate cellular or single channel responses in excitable cells. The resource comprises of two simulations. The first enables students to undertake virtual whole-cell voltage clamp experiments. They specify the duration and magnitude of a voltage waveform, the model returns simulated whole-cell current traces, from which they can determine, for example, the peak and steady state currents or time constants. The second simulates voltage-gated or ligand-gated single-channel currents. Students specify the membrane voltage, ligand concentration, and number of trials, with the model returning simulated single-channel current traces for analysis and interpretation.

This simulation promotes student knowledge and understanding of the biophysical properties of single ion channels or neurones. It enables students to undertake investigations that would be not be technically possible in a traditional undergraduate laboratory. This resource is available as an open educational resource from http://www.eng.utoledo.edu/~smolitor/download.htm

Bioinformatics (Weissman 2010) is a collaborative online virtual bioinformatics laboratory which provides the laboratory experience for a lecture-based bioinformatics course. Students are given weekly assignments (e.g. BLAST analysis of an individual gene), with – depending on the assignment – the same assignment for all students in a group or slight variations between students (e.g. different search parameters). After conducting their individual task, students work collaboratively online using Blackboard Vista to share results with their assigned group, discussing and interpreting their collective findings.

This laboratory is designed to foster active, enquiry-based collaborative learning and peer support. Students are not provided with detailed, cookbook-style instructions. They are required to learn to become proficient in searching for appropriate bioinformatics tools, reading and understanding documentation on these, and to ask their peers for help if they encounter problems. All the resources required for this laboratory are standard, open access, web-based bioinformatics tools and databases.

Critters (Latham and Scully 2008) is a virtual evolutionary biology world in which digital organisms are born, acquire the resources required to live, grow, mate, reproduce and die. It complements a lecture-based course in the discipline. After viewing the model or screenshots of the models organisms, students select one or more traits that might be influenced by an evolutionary mechanism. They formulate a hypothesis, and design and conduct experiments to test it. They are required to make a prediction before changing any parameter in the model.

This resource enables active, enquiry-based learning on a self-selected topic of interest within evolutionary biology and for students to undertake studies that would not be possible, due to time constraints, in a traditional undergraduate laboratory. Working in teams promotes both collaborative and peer-assisted learning. The opportunity to perform replicate runs enables sufficient data to be generated for statistical analysis to be taught. This resource is available as an open educational resource at: http://www.agentmodeler.org/edcritters/edcritters.html, other resources including an Instructor Manual, student guide and teaching exercise can also be downloaded.

E-Rat (Predavec 2001) is an interactive rat anatomy tutorial which provides students with knowledge and understanding of the reproductive anatomy of male and female rats. It replaces a conventional rat dissection practical. Students undertake the tutorial online in their own time. By clicking on structures mentioned in the text, students are provided with pictures, videos or animations of these structures. At the end of the tutorial, they complete a short quiz comprising of interactive questions randomly selected from a bank within the package.

This tutorial has advantages over a traditional cadaveric dissection in that it enables students to view intact structures from a range of animals, covering both sexes and all stages of development. They can work through it at their own pace, reviewing or returning to individual sections multiple times. Educationally, on completion, they are better able to associate structures with names and functions in comparison to students who are provided with this learning through conventional dissection laboratories. It provides an academically equivalent alternative to the use of animals in student education for those students who object to such use. The URL given for this resource (www.sci.monash.edu.au/biolsci/erat/) is no longer available.

Genetic Analysis (Breakey *et al*. 2008) is scenario-based, virtual genetic mutation laboratory which forms the laboratory component of an otherwise lecture-based genetic analysis course. Students complete individual scenarios online in their own time. The scenarios enable the screening and analysis of mutations in an imaginary model organism, with each scenario incorporating a series of experiments linked by a common concept. Students are provided with information (e.g. gel electrophoresis images, DNA sequencing output files) to interpret. They are then required to select an appropriate experiment (e.g. isolation of mutants, breeding of multiple generations or cross breeding) and answer MCQ questions on the information provided before they are allowed to proceed to the next stage in the scenario. Instant feedback is provided on their answers at each stage.

This series of virtual laboratories provides an active learning experience for students. They are required to make choices in the selection of individual protocols as in "real-life" research and to analyse and interpret data before moving onto the next series of experiments. It enables them to be provided with exposure to experiments and techniques that would not be possible, due to time constraints, in a traditional undergraduate laboratory. By using an imaginary model organism, the genetic techniques used in different model organisms can all be combined in a single scenario. Students are also not able to guess the experimental outcome of the laboratory experiment based on the model organism used, and instead, have to apply the concepts learned in lectures to their decision-making processes. This resource is available as an open educational resource at: http://dspace.jorum.ac.uk/xmlui/handle/10949/2854. Further information including guidance on using and adapting scenarios is available at: http://www.ls.manchester.ac.uk/undergraduate/facilitiesandresources/elearning/oerproject/. It was created using the using the authoring tool Scenario-based learning interactive (SBLi, http://www.sblinteractive.org).

Genome Island (Clark 2009) is a Second Life virtual science environment for studying genetics. The "Island" is organised into four areas, each containing opportunities to conduct experiments on a particular theme, for example, Mendelian Inheritance or molecular, bacterial and drosophila genetics. Students can either be given a list of experiments to complete or allowed to blaze their own trail around the island. For each of the 50 activities, students are provided with background information, a hypothesis and instructions on how to generate data. Data is collected, analysed and interpreted before students move on to their next task or assignment. There are also opportunities for self-assessment built into individual activities. Students can revisit individual areas for more advanced education as their understanding of a topic increases.

This resource promotes enquiry-based learning in either an Instructor or student-selected topic of interest. Online discussion fora promote collaborative learning whilst use of the virtual laboratory environment enables students to undertake investigations free of health and safety or time constraints. The resource is freely available as an open access resource at: http://slurl.com/secondlife/Genome/118/145/53 or http://maps.secondlife.com/index.php?q=genome+island&s=Places. (Free membership of Second Life http://slurl.com/secondlife/ is required)

Virtual Physiology of Exercise Laboratory (Dobson 2009) provides virtual simulations of classical human exercise physiology experiments (e.g. cardiovascular; lactate threshold; VO_2max; respiratory exchange ratio). It replaces traditional exercise physiology laboratories, forming the laboratory component of an otherwise lecture-based exercise physiology course. For each of the four virtual laboratories, students are provided with an online introduction to the topic. They then select their virtual participants, undertake pre-test health screening of these participants, select the most appropriate experimental test(s) and protocol(s), collect, analyse and interpret data. Post experiment, students are required to complete an online series of questions that build upon each other.

This combination of virtual laboratory with pre-laboratory and post-laboratory e-learning activities provides students with an active-learning experience which requires them to engage in experimental design and provides exposure to "real-life" research activities that they are unlikely to have to consider in a traditional undergraduate laboratory setting (e.g. participant selection and screening; test and protocol selection). In this regard, it could be viewed as providing a superior educational experience to a traditional laboratory, the caveat being that students do not receive exposure to, and experience of, working with actual participants or use of individual items of equipment. This resource is not available.

Joint use of virtual and traditional laboratories

The combined use of virtual and traditional laboratories in a course extends and enhances student learning beyond what could be achieving using either approach, the sum being greater than the individual parts. Depending on the learning objectives, virtual laboratories could be used before traditional laboratories as preparation for the latter, or vice-versa. For example, virtual laboratories can be used to apply the skills and techniques learnt in a previous traditional laboratory to real-world scenarios without the constraints of having to be proficient in those skills. Conversely, prior virtual laboratories can be used to enhance student engagement or increase knowledge and understanding in a subsequent traditional laboratory. Examples of best practice of the above are provided below:

Food Microbiology (Flint and Stewart 2010) is a virtual food contamination scenario. It is introduced to students midway through a laboratory course, once they have performed most of the laboratory tests or techniques included in the simulation. Students are required to work through a series of diagnostic steps, selecting an appropriate test at each stage, in order to identify the contaminating microorganism. Selection of the right test results in provision of the results and the ability to progress. Selection of the wrong test requires students to utilise the online feedback provided to inform their decision on their next choice of test, with students unable to move on until the right test is selected. To focus student's minds and prevent students just clicking on a test, each has a "cost" which accrues cumulatively throughout the scenario. This series of virtual tests provides students with information on the characteristics of the micro-organism. Students then use this information and consult reference material in order to identify the micro-organism. They also report on its significance to food contamination.

This virtual exercise provides students with an active, enquiry-based learning experience, training in experimental design, data analysis and interpretation, and promotes knowledge and understanding of microbiological diagnostic tests and microbiological contamination in a "real world" scenario.
It is developed using scenario-based learning interactive (SBLi, http://www.sblinteractive.org), an authoring tool which enables problem-based scenarios comprising of sequenced or un-sequenced activities to be constructed.

Genomes (Dalgleish *et al.* 2012) is an enquiry-based learning molecular genetics laboratory incorporating 'wet-lab' and bioinformatics tasks. Students are provided with a cloned human DNA sequence. They then use a range of molecular biological techniques (e.g. gel electrophoresis, PCR, Southern Blots) to estimate the size of the clone and its sequence, with individual practical tasks being carried out over four weekly wet laboratory sessions. Subsequently, students use bioinformatics tools (e.g. FinchTV trace viewing programme, http://www.geospiza.com/finchtv; UCSC Genome Browser http://genome.ucsc.edu/) to determine the location of their cloned sequence on the human chromosomes.

This resource combines an education and training in the use of molecular biological techniques with the use of bioinformatics tools. It also provides a "hands-on" real-life experience of the integration of 'wet-lab' and bioinformatics approaches in modern molecular genetics. This resource is available as an open educational resource from the GENIE Centre of Excellence in Teaching and Learning (http://www2.le.ac.uk/departments/genetics/genie).

Introductory Botany (Bonser *et al.* 2013) is a virtual microscopy laboratory in which student viewing and analysis of virtual botany slides is utilised to replace traditional microscopy laboratories. Using this virtual slide library enables students to, for example, examine the evolution of leaf tissue from primitive plants to evolutionary advanced angiosperms or compare and contrast leaf sections of different Australian species. The slides are extremely high-resolution scanned images of tissue sections. The underlying software (MicroBrightField) simulates the use of a real microscope, enabling students to change magnification or move a virtual stage to examine different areas of the slide. Permanent placement of an image of the whole specimen at the top of the slide, whilst simultaneously providing the capability to examine a section of tissue at closer magnifications, makes these virtual microscopy slides easier to navigate than traditional glass slides (Maybury and Farah 2010). Students can add comments or notes to the virtual slides, or return to and utilise the material for revision at a later date.

Virtual microscopy enables students to make observations and gain knowledge and understanding of the structure and function of cells, in this case plant cells and tissues, without the need to be proficient in preparing microscope slides (e.g. sectioning and staining plant tissue). These latter skills are acquired in traditional wet laboratories in earlier elements of the course. Slides can be accessed from the University of New South Wales Virtual Slide Repository (http://virtualslides.unsw.edu.au/)

Physiology e-learning (Dantas and Kemm 2008) combines a traditional human physiology laboratory with student online learning before and after the laboratory. Before the laboratory, students have to undertake tasks online, for example, predict the outcomes of the investigation or consider and explain the underlying mechanisms or concepts of their prediction. Post-laboratory session, students interpret the results obtained, review and revise their predictions, provide explanations for their results and resubmit this e-learning work. Automatic or tutor feedback is provided on both the pre and post-laboratory submissions. Topics for the practical sessions span human physiology from acid-base balance to the cardiovascular responses to exercises.

This combination of e-learning with a traditional laboratory promotes student engagement with the latter, active learning through hypothesis testing and the prediction of outcomes, and overall, an enhanced, deeper learning experience. This resource is not available.

Virtual cat dissection (Franklin *et al.* 2002) is a computer simulation of the dissection of a cat cadaver. This simulation enables students to undertake a dissection, using a virtual scalpel, of a virtual cat cadaver to explore the structure and function of the major mammalian body systems. Students can opt to use either the simulation or a part-dissected cat cadaver or both methods of learning, for example, the cadaver to handle and explore major organs and tissues followed by the virtual dissection to review and reinforce their understanding of the systems.

The use of cats in scientific research in the UK is negligible (n = 247, 0.006% of total, Home Office 2013) and therefore use of this particular simulation would not benefit student education in the UK. However, it provides an excellent example, if the simulation was of a more commonly used species of research animal (e.g. rodent, see E-rat, Predavec 2001), of how virtual and traditional laboratories can be utilised in parallel to enhance student learning in the anatomy and physiology of body systems. Further, given that many students do not go onto careers in scientific research and therefore do not need to acquire dissection skills, providing students who object, for moral reasons, to the use of animals or animal tissues in their education with an academically equivalent alternative is good practice. This resource is not available.

A full list discovered resources and links to each can be found in the Appendix.

6. Use of virtual laboratory tools to complement and supplement traditional hands-on laboratory learning

Both virtual laboratory tools and traditional hands-on laboratories have benefits and limitations when used in isolation. For example, training in basic laboratory skills or hands-on experience in the use of individual items of experimental equipment cannot be provided with virtual tools. However, the latter are excellent in providing enquiry-based, contextualised learning. Thus, when used in parallel, they complement and enhance the learning from the other, whilst also catering for or covering the limitations of the other format of delivery.

Nonetheless, the full potential of virtual laboratory tools will only be realised if course providers rethink their overall practical provision. With the recent explosion of scientific knowledge, many programmes are suffering from content overload. Scientific information is readily available online. What employers increasingly require of graduates is the ability to search for, acquire, interpret and apply scientific and mathematical knowledge (ABPI 2008; CBI and Pearson 2013). Laboratories, whether traditional or virtual, play a critical role in this learning. At level four, students could be provided with training in basic laboratory skills, techniques and safe working practices in traditional laboratories. The parallel use of virtual laboratory tools would enable students to make mistakes in safe environments, to repeat studies and to learn from their mistakes before undertaking more complex traditional laboratories where there is the potential to cause harm or only one chance to undertake the study, for example, the use of human patient simulators in preparation for a human physiology or pharmacology laboratory (Lloyd *et al*. 2006). At level five, there should be a shift from passive, protocol-driven sessions towards active, enquiry based learning, incorporating experimental design and the application of knowledge to “real-world” scenarios in preparation for level six or final year research projects. It would also address employer’s demands for “research ready” or “work ready” graduates” (Office of Life Sciences 2009; CBI and Pearson 2013). This learning could be achieved either through the use of investigative wet laboratory mini-projects (Bevitt and Wilson 2009; May 2014) or virtual laboratory scenarios (Flint and Stewart 2010).

However, maximal educational benefit and student learning will only be realised if laboratory tools, whether virtual or traditional, are not utilised in isolation but in parallel with other online or technological resources for example, pre-practical and post-practical exercises or quizzes (Dantas and Kemm 2008; Langton and Macmillan 2008; Sancho *et al*. 2006), online discussion groups (Harris 2012), virtual laboratory manuals (Felder *et al*. 2013; Michaels *et al*. 2005; Olivo 2003), access to supplementary digital resources in traditional laboratories through the use of tablets or similar devices (Morris *et al*. 2012) or the use of integrated digital learning packages, for example LabTutor (Felder *et al*. 2013) or eBiolabs (Hughes *et al*. 2012).

7. Recommendations

- The use of virtual laboratory tools within UK undergraduate degree programmes in the Biological Sciences should be substantially increased. These should not be utilised to replace traditional laboratory sessions, but should be fully integrated alongside these within programmes to complement and supplement student learning from both traditional laboratories and other teaching sessions.

- Existing traditional laboratories should not just be digitised. Rather, the content and format of new virtual laboratory tools should be properly planned, taking into account the intended learning outcomes of the resource, making full use of available digital tools, ensuring that it is fully integrated with other elements of the course, and builds on the knowledge and skills gained from these. These should not be protocol driven, but provide a high-quality enquiry-based learning experience. The tool should be capable of full integration within institutional virtual learning environments (VLEs) and, as far as possible, future technology proofed. It should cater for different student learning styles.

- In developing and incorporating virtual laboratory tools into their programmes, institutions should consider the intended learning outcomes for their overall practical provision and the development of practical and generic skills throughout the programme. Level four could encompass recipe driven virtual and traditional practicals. Level five would build on this knowledge, with a shift towards active, enquiry-based, collaborative learning (virtual and 'hands on'), incorporating experimental design in preparation for level six or final year research projects. Such a scheme would give students greater ownership of their learning, facilitate the development of key employability skills (resilience, problem solving, self-reliance, team-working, application of knowledge). It would also address Society of Biology criteria for accredited degree programmes (Society of Biology [n.d.]) and employer demands (Office of Life Sciences 2009; CBI and Pearson 2013).

- Any developed resources must be of high quality, both educationally and technologically. Current students are the "Digital Generation"; advanced technologies play a big part in their lives, they are used to high quality digital resources and games. Therefore, resource development should be a collaborative partnership between discipline specialists, students, learning technologists and educationalists, and potentially, commercial concerns.

- Development of new virtual laboratory tools will require substantial resource. It is unlikely that initiatives, such as the establishment of HEA Centres of Excellence in Teaching and Learning (CETL), will be repeated. However, consideration should be given by funding bodies for funding schemes to develop virtual laboratory tools. This may require the establishment of collaborative partnerships between discipline specialists and commercial educational resource providers. Institutions should also provide educators with time and resource to develop and integrate virtual laboratory tools within their curricula.

- A community of practice should be established to share knowledge, best practice and tools. Developed virtual laboratory tools could be shared, either as open educational resources (OERs) or as commercially licenced entities.

- Educators and product developers should undertake properly controlled, full evaluations of the effect on student learning and impact of their interventions, and publish these.

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Appendix: Discovered resources

Beverage-Agarose Gel Electrophoresis (BAGE) (https://jshare.johnshopkins.edu/scunnin9/BAGE_Page/index.htm) virtual gel electrophoresis tools (Cunningham *et al.* 2006).

Cardiac Function (http://medicine.missouri.edu/mpp/content/faculty/davis-m/Models/pvmodel.html) Simulation of cardiac function (pressure/volume) (Davis and Gore 2001).

Cellular Neurophysiology (http://www.eng.utoledo.edu/~smolitor/download.htm) simulations of excitable cells (Molitor *et al.* 2003).

Critters (http://www.agentmodeler.org/edcritters/edcritters.html) virtual evolutionary biology world (Latham *et al.* 2008).

CogLab (https://coglab.cengage.com/info/ie.shtml) simulation of 50 cognition experiments (Bish and Schleidt 2008).

Cyber Physiology (http://www.cyber-anatomy.com/product_CPSBS.php) Commercial simulations of cardiac, respiratory and kidney function (Samsel *et al.* 1994).

Digital Slidebox (http://www.digitalslidebox.com/login.php) Digital slide management software (MacMillan *et al.* 2009).

EcoLab (http://www.ramas.com/teaching.htm) Digital resources and models for teaching ecology (Shultz et al. 1999).

Foodworks (http://www.xyris.com.au/default.html) Food composition and nutrient analysis software (Macaulay *et al.* 2009).

Genetic analysis (http://dspace.jorum.ac.uk/xmlui/handle/10949/2854) scenario-based, virtual genetic mutation laboratory. Further information at: http://www.ls.manchester.ac.uk/undergraduate/facilitiesandresources/elearning/oerproject/ (Breakey *et al.* 2008).

Genome Island (http://slurl.com/secondlife/Genome/118/145/53) Genetics Second Life virtual science environment (Clark 2009).

Histoviewer (http://anat-microscopy.ana.au.dk/Histo/histo.php) Interactive virtual microscope (Sander and Golas 2013).

Introductory Botany (http://virtualslides.unsw.edu.au/) repository of virtual botany slides (Bonser *et al.* 2013).

KaryoLab (http://learninginteractive.org/karyolab.htm) simulation to teach karyotyping (Gibbons *et al.* 2004).

Modular Digital Course in Undergraduate Neuroscience Education (MDCUNE) (https://mdcune.psych.ucla.edu) website of neuroscience Open Access Resources (Grisham 2009).

Mutate (http://webs.uvigo.es/acraaj/MutateWeb/Mutate.htm) Simulation of genetic mutation (Carvajal-Rodriguez 2012).

NeuroDynamix (http://www.neurodynamix.net/home) Simulations of neural function (Crisp 2012).

Neurons in Action (http://neuronsinaction.com/about/nia) Compilation of cellular neurophysiology digital tutorials and Neuron (http://www.neuron.yale.edu/neuron/) simulations.

Neuroscience tools (http://www.mccauslandcenter.sc.edu/CRNL/tools) Digital tools for analysing neuroscience data (Bish and Schleidt 2008).

Oxsoft Heart (http://models.cellml.org/cellml) simulation of cardiac cell electrophysiology. Many other physiological simulations available at this site (Le Guennec *et al.* 2002)

Photosynthesis in silico (http://www.e-photosynthesis.org/) simulations of photosynthesis (Russell *et al.* 2004).

PhysioEx (http://www.physioex.com/) Commercially available human physiology simulations (West and Veenstra 2012).

Plant, Pathogens and People (http://www.ppp.uiuc.edu) Digital resources and experiments for teaching plant pathology (Eastburn and D'Arcy 2006).

Proteomics (http://sourceforge.net/projects/jbf/files/?source=navbar) simulations for teaching proteomics (Fisher *et al.* 2012).

Sheffield Bioscience (http://www.sheffbp.co.uk/sbpmain.htm) Simulations of physiological and pharmacological function (Dewhurst *et al.* 1994).

Simbio (http://simbio.com/) Commercial repository of virtual biological sciences laboratories (Meir *et al.* 2005).

Simulator for Neural Networks and Action Potentials (SNNAP) (http://nba.uth.tmc.edu/snnap/) cellular neurophysiology simulation (Av-Ron *et al.* 2006).

Sniffy, the virtual rat (http://wadsworth.cengage.com/psychology_d/special_features/sniffy.html) simulation of psychological studies in rodents.

Stereoscopic images of Speech structures (http://www.shs.uiuc.edu/shs300/default.htm) 3D anatomical images of respiratory and speech structures (Perry *et al.* 2006).

Synaptic Physiology (http://medicine.missouri.edu/mpp/content/faculty/davis-m) simulations of synaptic and neuromuscular physiology (Davis 2001).

Virtual Heart (http://thevirtualheart.org) information and simulations of cardiac function (Bartocci *et al.* 2011)

Virtual Microscopy (http://www.lab.anhb.uwa.edu.au/mb140/scope/scopefrm.htm) virtual microscopy and repository of virtual histology slides (Maybury and Farah 2010)

Virtual Patients (http://www.virtualpatients.eu/) repository of virtual patients (Lehmann *et al.* 2010)

Virtual Rat (http://spider.science.strath.ac.uk/sipbs/page.php?page=software_sims) Simulation of pithed rat experimental preparation. Other in-vivo and in-vitro simulations available (Sri Nageswari *et al.* 2004).

Virtual Rocky Shore (http://www.esafari.co.uk/Resources/vrs/) virtual ecological environment (Stafford *et al.* 2010)

Whole Brain Atlas (http://www.med.harvard.edu/AANLIB/home.htm) images of normal & diseased brains (Bish and Schleidt 2008)

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ISBN: 000-0-0000000-00-0

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