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Designing online laboratories for optimal effectiveness: undergraduate priorities for authenticity, sociability and metafunctionality

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Over the past two decades, growing numbers of universities worldwide have developed online laboratory facilities for teaching science and engineering. Remote experiments (REs)¹ give students access to live data from – and, typically, control over – a distant real-world instrument or apparatus. Virtual experiments (VEs)² present students either with computer-generated emulations of devices or phenomena or with reconstructions of real-world experimental setups that rely upon genuine data. In recent years some VEs have even employed fully-realised virtual environments in Second Life³ and Unity 3D.⁴ While such distance approaches to practical work present key advantages over conducting experiments ‘in the flesh’,⁵ doubts persist over whether they can convey the full benefits of the traditional on-site lab experience.⁶ As early proofs of concept have given way to more mature implementations, a growing consensus has arisen that remote experiments^{7,8,9,10} and, to a lesser extent, virtual ones^{11,12} deliver comparable learning outcomes for students. However, relatively little attention has been paid to which elements of practical science work are valued most by undergraduates in different scientific fields, to what extent prior expectations impact their performance in online labs, and how such knowledge can inform the design of future remote and virtual experiments.

Our research programme focuses on the role three key aspects – *authenticity*, *sociability* and *metafunctionality* – play in student perceptions of online experiments and on their effectiveness as tools for practical science instruction. In order to prepare students to one day find solutions to complex global issues, pedagogical theory suggests a prerequisite is delivering authentic learning experiences, lest the practice of science seem divorced from everyday life. Yet what do students consider ‘authentic’ in terms of remote and virtual investigations? Realistic interfaces? Relevant scenarios? Reliable data? Should online labs concentrate on broad conceptual understanding or aim to develop specific experimental skills and procedures?

The application of social modes of learning to online experiments exhibits similar dichotomies, as fostering collaborative skills must be balanced against accommodating the needs of solitary learners. Since evidence indicates that interpersonal interactions during lab work improve performance on assignments,¹³ how should we ensure these still occur when students aren’t co-located in the same physical space? Forum-led discussions?¹⁴ Instructor-led live laboratory sessions?¹⁵ Ad-hoc synchronous channels like Skype? For a significant fraction of the population – and many opting for distance learning – the default

of an assumed-collaborative, constructivist approach to science is at odds with their desire to pursue studies independent of their peers.^{16,17} For such students and those who are socially-averse, the non-physicality of remote and virtual experiments may in fact reduce anxieties over doing practical science.

Metafunctionality describes features of online laboratories that would be difficult or impossible to implement in a traditional (i.e., on-site) scientific setting. Virtual labs might include the ability to freeze, rewind, or fast-forward through experimental procedures, to save experimental states to revisit and modify later, to interrogate results at a variety of physical scales, or to simulate non-ideal scenarios for training purposes. Remote labs could likewise be enhanced by the provision of additional sensory feeds, augmented reality (AR) overlays, or other live data visualisation approaches. As none of these features are essential to conduct scientific investigations, we wanted to establish whether students felt they would actually use and derive genuine benefit from them.

A large-scale ($n=1140$) study was undertaken during 2014 at The Open University (OU), UK, one of Europe's largest distance learning institutions, involving undergraduates enrolled in two eight-month-long science modules – one built for second-year students and one for third-years. Each cohort engaged with a selection of online experiments in the course of their module work, the overall sample representing 5 scientific disciplines (chemistry and analysis; environmental science; geology and Earth science; health and life sciences; physics and astronomy) and encountering 26 unique experiments. The full list of these experiments – many of which have been made available as part of The OpenScience Laboratory (www.opensciencelab.ac.uk) – is summarised in *Table 1*.

Our data collection schedule included multi-stage survey instruments (comprising Likert-type, ranking, and open-ended questions), discipline-specific focus groups, and semi-structured interviews with individual students and the designers of the remote and virtual experiments they encountered. By eliciting student preconceptions of online labs and tracking their subsequent opinions after each study block, we were able to assemble a clearer picture of how their expectations for practical work had either been met or confounded in each instance. An examination of the corresponding demographic data and assignment marks allowed us to separate trends in attitudes by sub-group membership and to check whether specific beliefs about online experiments correlated significantly with assessed outcomes.

Table 1: Online experiments examined in this study, by discipline and type

Name	Discipline [number of students responding]	Type [data]	Description
axial field ISE	physics/astro. [n=64]	VE [real]	an ‘interactive screen experiment’ to map the axial field of a short coil using a Hall probe
BOD (biochemical oxygen demand)	chemistry [n=89] enviro. sci. [n=144] geology [n=75] health/life sci. [n=119]	RE [real]	a remotely-monitored experiment where students ‘tune in’ to streaming webcams to collect/plot live data from 6 BOD monitors
Compton 3D	physics/astro. [n=64]	VE [artf.]	virtual environment (a lab setting including an annotated Compton device) explorable by first-person perspective in Unity 3D
Compton scattering	physics/astro. [n=64]	RE [real]	a LabVIEW remotely-operated Compton device located in a laboratory at The Open University
Compton scattering planning tool	physics/astro. [n=64]	VE [real]	Compton scattering effect simulator used to plan/prepare for live remote experiment
DNA quantitation	chemistry [n=73] health/life sci. [n=104]	VE [real]	virtual spectrophotometry, including dilution preparation via virtual micropipettes
fine-beam tube ISE	physics/astro. [n=64]	VE [real]	an ‘interactive screen experiment’ from which the charge-to-mass ratio of the electron can be derived
histology lab	health/life sci. [n=96]	VE [real]	virtual 360° panoramic lab space, annotated with overlays, and linked to a virtual histological microscope for rat adipose tissue inspection
human RVP	health/life sci. [n=181]	VE [real]	human rapid visual processing task via software
magnetic field of short coils	physics/astro. [n=64]	VE [artf.]	magnetic field line visualiser displaying artificial data
Mars orbital viewer	chemistry [n=38] geology [n=67] physics/astro. [n=83]	VE [real]	virtual planetary feature viewer for Mars, allowing students to examine topology, thermal & IR data sets
microbiology of water	chemistry [n=89] enviro. sci. [n=144] geology [n=75] health/life sci. [n=119]	VE [artf.]	bacterial colony incubation, aerobic colony count, coliform & enterococci detection, MPN, pathogen confirmation
NMR autosampler	chemistry [n=116] physics/astro. [n=90]	VE [real]	virtual NMR autosampler for generating ¹ NMR spectra

NMR ISE	chemistry [n=116] physics/astro. [n=90]	VE [real]	an 'interactive screen experiment' whereby students familiarise themselves with NMR operation
pesticide analysis with GC-MS	chemistry [n=89] enviro. sci. [n=144] geology [n=75] health/life sci. [n=119]	VE [real]	virtual gas chromatography / mass spectrometry
physiology lab	health/life sci. [n=96]	VE [real]	virtual 360° panoramic lab space, annotated with overlays, and linked to a virtual spectrophotometer for rat adipose tissue analysis
PIRATE robotic telescope	physics/astro. [n=77]	RE [real]	a 17" remotely-operated semi-autonomous telescope located in Mallorca, Spain
PIRATE simulator	physics/astro. [n=77]	VE [artf.]	a control interface identical to the one used on the robotic telescope, generating 'night sky' image frames from star catalogue data
quantitative HPLC	chemistry [n=73] health/life sci. [n=104]	VE [real]	virtual high-performance liquid chromatography / mass spectrometry
rat training laboratory	health/life sci. [n=181]	VE [artf.]	virtual animal feeding, weighing and behavioural modification (i.e., a sustained attention task)
sedimentary Cyprus	geology [n=170]	VE [real]	virtual hand specimens of rocks (photographed in 360° and at multiple zoom levels)
spectrophotometric analysis of nitrates	chemistry [n=89] enviro. sci. [n=144] geology [n=75] health/life sci. [n=119]	VE [real]	virtual spectrophotometry, including standard solution preparation, calibration curve plotting and analysis of unknown within working range of plot
virtual meteorite microscope	chemistry [n=38] geology [n=67] physics/astro. [n=83]	VE [real]	virtual petrographic microscope for examining high-resolution thin section scans under plane polarised light & crossed polars
virtual petrographic microscope	geology [n=170]	VE [real]	virtual microscope for examining high-resolution thin sections under PPL and XPL
water hardness determination ISE	chemistry [n=89] enviro. sci. [n=144] geology [n=75] health/life sci. [n=119]	VE [real]	an 'interactive screen experiment' for performing a virtual titration, including initial laboratory glassware selection
virtual animal research facility	health/life sci. [n=96]	VE [real]	virtual mock-up of a facility for selecting/researching test animals

Our mixed-methods approach included statistical tests using SPSS and thematic analysis in NVivo, both of which revealed significant differences in perceptions held between those studying different subjects, between males and females, and between those at different course levels. Perceived *authenticity* was most strongly influenced by course level and subject strand. Confirming our 2013 research findings,¹⁸ we noted that despite second-year students reporting fewer anxieties regarding practical work, they exhibited significantly more scepticism than third-years for the realism, relevance and reliability of online experiments both at the pre-engagement stage and at module's end. Geologists and environmental scientists were also significantly less likely to find online labs convincing or beneficial, whilst the biologists held by far the most positive views in this regard of any strand. Chemists and physicists expressed mixed impressions which often divided by whether they viewed the module content as essential to developing skills for future employment. Of the two, however, chemists were marginally less accepting of remote and virtual experiments as authentic learning experiences. A contributing factor here is the inverse relationship we noted between prior science experience and perceptions of online labs as irrelevant or unreliable – e.g., on the whole physicists and chemists had the most prior (practical) science exposure at school or the workplace and environmental scientists and geologists the least.

Attitudes towards *sociability* showed a gender division, with females being significantly more likely to harbour initial anxieties over practical work, expressing greater expectations for skill gains in collaborative work and confidence-building, and holding more favourable attitudes than males towards the potential social benefits of distance learning approaches for science. These results echo earlier studies which found that females in traditional classroom or laboratory settings experience elevated levels of Mallow's 'science anxiety'^{19,20,21} and could potentially benefit from less overtly

competitive and regimented approaches to science instruction.²² From a course level standpoint, second-years were significantly more likely to feel that virtual and remote experiments made it harder to teach collaborative skills but sufficiently accommodated solitary learners. In this area there were fewer key differences observed by discipline, although again the biologists were the most positively inclined, willing to accept that online experiments make practical science more enjoyable, encourage students to try different approaches, and accommodate solitary learners.

In the course of identifying which aspects of using online labs were most valued by participants, large points of commonality were also found. Again on the *authenticity* front, one surprising result we encountered was a nearly universal rejection of the suggestion that heightened realism in virtual or remote experiments should be achieved through more photorealistic interfaces. Even amongst many students who had indicated that they wished online labs could feel more ‘real’, the desire expressed was still for clear, simple controls. In contrast to this stated desire for simplicity in the actual interface was the high value students placed upon having access to so-called ‘messy’ (i.e., not modelled, sanitised or computer-generated) data and moreover the ability to make genuine mistakes in virtual experiments – as long as these were subsequently addressed by instructional prompts in the software itself. Such comments support Balamuralithara and Woods’ observations regarding the need for clear objectives in lab work and the recognised drawbacks of simulated data.²³

Concerning *sociability*, the most widely expressed sentiment was a desire for enhanced synchronous social learning provisions (both student-to-student and student-to-tutor) in virtual and – somewhat surprisingly – remote laboratories. Most of those polled seemed to have an innate sense that an essential component of practical science is the ability to bounce ideas around and get immediate feedback that might resolve minor

mental obstacles to progressing through an experiment or procedure – something that is lacking in the majority of virtual labs, often designed as they are to be single-user experiences. When students were queried as to the value of the official module discussion forums as a way to get assistance, the response was almost without exception that forums were only a destination of last resort. To be clear, this was not because they considered them devoid of value – very much the opposite – but because they dreaded both the interruption to their study flow and the time investment that a trip to the forums represented for them. When during interviews the researcher proposed adding a synchronous chat facility to the interface of virtual experiments, the notion was greeted enthusiastically, with the usual caveats that it should have a Skype-like ‘invisibility’ option for when students weren’t feeling particularly social. When it came to remote experiments, students felt that while Skype or similar voice audio tools worked fine for coordinating with lab partners, they did not magically transform an interface designed to be used by one person at a time into something that fostered genuine collaboration.

Conclusions regarding *metafunctionality* were more difficult to draw from the Likert-type responses as only a few of the experiments the study sample were exposed to actually supported such features as yet. Some attitudes came across quite clearly, however. These undergraduates did not perceive much value in having the ability to dynamically alter the flow of time in virtual experiments and most did not want experiments to take a ‘realistic’ amount of time to complete. Whilst a handful of students opined that a ‘real time budget’ or ‘real time clock’ might prove useful if displayed in the interface as a reminder of the realities of time-consuming lab work or repetitive tasks, they did not imagine they would want to actually experience same outside of paid employment. What precipitated from the interviews and focus groups, however, was a strong desire for certain classes of metafeatures in virtual labs – predominantly ones that would allow them to safely test out

potentially risky procedures or to learn to troubleshoot non-ideal scenarios that they might later encounter in a real-world scientific setting. Even so, most of the focus group participants conceded that the existing time pressures of practical work would likely preclude them from taking full advantage of such features unless their coursework was explicitly adapted to make use of these enhanced modes. We conclude that any worthwhile implementation of metafunctionality in online experiments will not bear significant learning dividends without a simultaneous rebalancing of instructional design considerations.

The findings of this study provide insights into student perspectives of online labs and clearly illustrate how the same experimental investigation may be viewed quite differently by students across various disciplines. Our paper goes on to provide recommendations for tailoring specific classes of virtual and remote experiments to the expectations and priorities of the intended users and thus secure improved student engagement and outcomes. Our results will be of especial interest to the designers of online scientific investigations and to educators who expect to deploy them at the undergraduate level.

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