Breaking down the Laboratory Supertype Conflation

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***Abstract*— This Research Full Paper analyses a dissonance in the application of accepted educational theory to development and research on laboratories in education. Most existing research has tended to conflate multiple constituent factors, resulting in an inability to appropriately determine which specific factors are the cause of observed variations in learning outcomes, and an inability to reliably interpret the external validity of the research outcomes.**

We begin with an outline of the supporting educational theories that underpin our understanding of laboratory education. We then identify notable examples in the literature where multiple variables, such as the user interface and access modes, have been conflated into laboratory 'supertypes' and are not investigated independently. These supertypes reflect the most common variable combinations: 'proximal laboratory, hands-on interface', 'remote laboratory, rich contextual interface', and 'simulated laboratory, decontextualized interface', referred to as hands-on, remote, and simulated/virtual respectively.

We then investigate the impacts of this conflation – in the context of examples, this conflation limits the generalisability of previous results and obscures potentially rewarding avenues of future research. Finally, we present methods by which research may be conducted to investigate technically simpler directions of interface decoupling, the results of which may motivate the investigation of more challenging pairings.

Keywords—educational; laboratory; interface; remote; virtual; simulation; research; haptic; computer-mediated; rigor;

I. Introduction

The use of non-traditional laboratory experiments, (e.g. remotely controlled equipment, recorded experiments, or simulations) in engineering and science education has seen increasing interest over the past few decades. Initially this existed in a nascent period of 'what can we do technically' research, typified by technical specifications and lessons-learned system papers, where the research was being conducted by engineers looking primarily at overcoming the engineering difficulties of their implementation. After such laboratories became known to be feasible and believed to be scalable, interest arose in the educational validity of non-traditional labs, with several theoretical models being proposed and then tested by comparative studies contrasting one laboratory version against another – which is the predominant state of research in the field today.

Early works comparing laboratory implementations used low dimensional data and simple analyses, comparing selected outcomes such as grades and/or student attitudes toward the formats. [1]–[3] One of the first and certainly the most highly cited paper on increasing the breadth of analysis of non-traditional laboratories is Nickerson et al's [4] "A Model for Evaluating the Effectiveness of Remote Engineering Laboratories and Simulations in Education". This model codified several variables to consider when designing or evaluating laboratories, highlighting several aspects of laboratory design which may impact the outcomes of those laboratories. The current paper is primarily interested in the Experiment Interface, Lab Technology, and Lab Frame components of this model, reproduced in Figure 1.

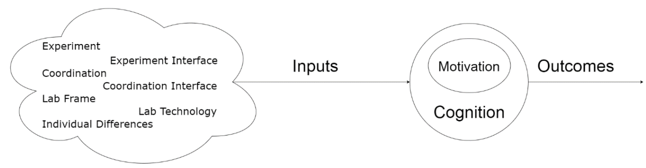

Figure 1: Nickerson et al's [4] inputs and outputs model

Experiment Interface refers to the connection between the user and the equipment – it is the means by which the user manipulates input variables and observes outputs. An example of this might be a centrifuge incorporating a strain sensor, where one version of the laboratory involves turning a physical speed dial by hand (an input variable) and reading a digital panel displaying current strain (an observation). Manipulating this design variable might involve connecting the centrifuge controller and sensor to a computer, such that the user now manipulates the equipment by using a mouse and keyboard, and makes observations on the computer monitor rather than the panel. It also incorporates other changes to this connection, for example changing the above laboratory so that the user instead inputs the desired strain, and observes the speed the equipment reaches to achieve it.

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Lab Technology refers to particular archetypes of instructional laboratory design – originally including proximal/traditional laboratories, remote laboratories that provide access to real equipment, and simulated laboratories which use a computer model of reality. The authors also include a position between remote and simulated, 'recorded real'. This type of lab technology is built on a recording of input/observation sets from a real instance of the laboratory, and then presents the matching results when requested later. An example implementation of this type is the MSOL project from Stanford [5].

Lab Frame refers to the user's perception of what the lab technology is, whether or not such a perception is accurate. Lab Frame represents a constructionist view of education, where student perception governs their learning. For example, it is quite feasible that a remote experiment, which involved real equipment, is perceived by a student as a simulation, or indeed vice versa.

It might be more intuitive to describe these ideas of lab technology and frame a little differently. The primary concern when differentiating between the three or four versions is where the data from the experiment is coming from – that is to what extent does it reflect real world behaviours? Thus, the laboratory mode is important, whether from local equipment, remote equipment, or some computer model, and laboratory mode perception being the user's idea of the same.

This paper has two primary objectives. The first is to use a sample of research in the field to show how these clearly differentiated variables are often not examined separately, and to examine what impact this lack of differentiation has had on their resultant interpretation of the research outcomes. The second is to discuss different methods by which research into non-traditional laboratories may be designed to decompose these supertypes into their constituent elements, while respecting the time, and cost constraints which apply to all research design.

II. The Importance of Interface

As we will see from the existing literature, researchers have a tendency to pair proximal laboratories with haptic interfaces, and remote or simulated laboratories with computer-mediated interfaces. However, even within the basic categories of the reference model, distinctions exist which may be differentiated and analysed independently. Haptic interfaces in the traditional setting are inherently defined by the equipment being used – but different equipment with different methods of interaction may be substituted to perform the same tasks. Of more obvious relevance are the differences between alternate computer-mediated interfaces. The familiar implementation of a remote laboratory involves paired UI components such as text input boxes, sliders, dials, toggles etc. which correspond to robotic controls on the laboratory rig. For example, a rig may have a 'height' parameter, which is controlled via a number input. The observational component of the laboratory might be text output, or a richer interface involving video or animation output. Interfaces for simulated laboratories tend to follow a similar process, however instead of pairing with physical controls, they instead pair with inputs on the simulated model, which may or may not directly map to some real-world implementation.

The reason that interface is such an important consideration when designing and comparing laboratories is twofold – the first is that within a single laboratory (especially computer-mediated laboratories), there exists the possibility of choice. It is not the case that for a specific laboratory only one possible interface may be used. Even if we limit ourselves to a naïve implementation, a height control might be the number input previously described, or it might be a slider. It may even be a control overlaid on a video feed where the mouse or touch input simulates a hand moving a 'physical' control surface up or down. The implication of this is that interface may not be assumed – it must be designed. The second is the idea that interface matters for education. This idea is heavily supported by research in a plethora of different fields and contexts – for example, Schunk [6] draws on constructionist theory from Piaget among others to describe learning theories which place great emphasis on the contexts for learning in which interface is a primary component. Swan [7] reviews several studies in online education which lend specific weight to these theories in a closely related field. We can conclude that interface is therefore a critical component of laboratory, designs and should be investigated accordingly.

III. Super-types in the Literature

In significant and otherwise rigorous research papers which compare traditional and non-traditional laboratories, the distinct variables of experiment interface, laboratory technology, and laboratory frame are not controlled for, analysed, or in some cases even reported at all. Instead, research into these different types of laboratories allow them to collapse into 'supertypes', which are most commonly referred to as hands-on/proximal/traditional, remote, and simulated laboratories. Each supertype is then the conflation of all three of the design aspects; e.g. the remote supertype encompasses a computer interface (with no visibility of the equipment except through this interface), equipment that is remote, and student perception that the equipment is real but remote. These conflations and the combinations they 'miss' are indicated in Figure 2.

To illustrate this tendency towards conflation, a number of research papers will be examined as case studies. It is worth noting here that to date no known research has been conducted into the idea from Ma & Nickerson [8], which eventually formed a part of the evaluative model: "Belief May Be More Important than Technology" - it is entirely possible that the actual laboratory mode is irrelevant in the face of the students' perception of it. It is also quite possible that the students' perception of the laboratory will be shaped in large part by the interaction between the other components in the model, and is therefore an intermediate variable rather than an independently controllable input.

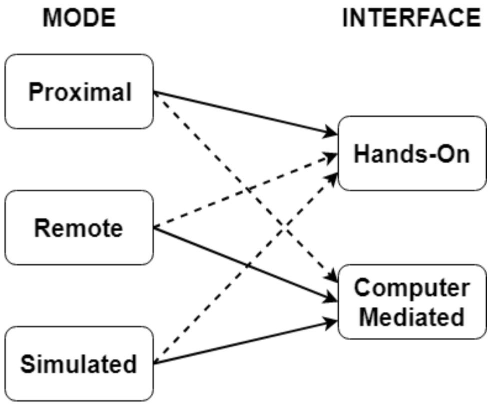

Figure 2: The relationships between mode and interface, with 'missing pairs' indicated

In light of this intangibility, the lack of research is not surprising; however, it should be considered when attempting to understand the results of laboratory research. This analysis primarily concerns the conflation between experiment interface and laboratory mode, where research assumes the two may not, or need not, be investigated independently.

For reasons of experiment design constraints and technical difficulty, hands-on experiments typically retain their usual haptic interfaces, remote experiments use a setup involving a digitally mediated interface and more recently a video feed to the equipment, and simulated experiments involve a similar digitally mediated interface but no such feed. It is certainly valid to say that such setups are easier to implement for each particular supertype. It however ignores truly significant possible avenues for research when researchers assume the supertypes must involve specific elements from the above design characteristics – such avenues will be discussed later in the paper.

A. Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories [9]

Interestingly, [9] comes from the same research team which developed the original model, and was published well after – yet it explicitly references the hands-on/remote/simulated supertypes common throughout the literature. It presents a proximal laboratory with a haptic interface, contrasted with a remote laboratory with a computer-mediated interface, and a simulated laboratory with a computer-mediated interface. Also important is the inconsistency in interfaces between the remote and simulated formats – as implied by their earlier work on these laboratories [10]. The study measured various intermediate and final outcomes from students during the experiment, including time spent, data collection method choice, test results, and satisfaction.

The impacts of the conflation in this study relate to the confounding of results, improper generalisation of results, and obscuring potential future research. The study indicated lower test scores for the simulated supertype – however the simulation interface required approximately 40 minutes of setup time, where the remote and hands-on supertypes were both under 20. The simulation students then spent less time on each subsequent task than hands-on or remote students, with the authors speculating, "*It could be that students in the simulation condition saw less benefit in exploring the data thoroughly because it was simulated rather than real*." [9, Sec. 2.2.1] Without aligning the interfaces between all three modes, this cannot be determined – it may simply be that in a limited-time laboratory class, students did not have as much time to spend on further activities, or alternatively a change in interface meant fewer distractions.

The paper also notes students tended to operate as a group more often in the hands-on type, with the authors speculating this may have been due to interface differences. The result of higher outcomes for group hands-on students, especially where the group-individual difference was higher than the group-individual difference in remote and simulated types, was speculated to be related to the ease of group collaboration when using a haptic interface, where the computer-mediated interface did not easily support it. Again, without aligning the interfaces between different modes, these questions may not be definitively answered.

B. Effects of laboratory access modes upon learning outcomes [11]

Paper [11] was published prior to the publication of the model; however, we may apply the model to evaluate the experimental design of the study it describes. Again, we see the complete hands-on/remote/simulated conflation presented in contrast, with the study measuring against various desired learning outcomes and student perceptions. Here the remote and simulated versions shared a common interface.

In presenting the rationale for the study design, the authors discuss the need to unify the interface between the remote and simulated versions, neither of which involved rich media making the unification relatively simple. However, it was believed the identified effects could be extrapolated onto the hands-on supertype, which violates the contextual learning principles which underpin modern educational research – that cognition is a systemic process in which it is the interplay of variables, not their isolated impact, which has the strongest effect on the outcome. The study indicated mixed results for various learning and affective outcomes, with various areas lending themselves to certain supertypes. This invalid extrapolation or otherwise generalisation of results is a common issue faced in engineering research, as indicated by Borrego [12, Sec. IV A].

This study may serve to highlight the importance of the separation of contributing elements – its design enabled it to detect a difference in reaction and outcomes between simulated and remote laboratory modes and specifically target the mode as the cause of this difference by controlling the interface as identical between the two. This control not being present for the hands-on supertype, it is therefore undetermined whether the benefits and drawbacks linked to either choice are caused by the mode, or by the interface.

C. *Physical versus virtual manipulative experimentation in physics learning [13]*

This paper is different to the prior papers in that it is from the science field rather than from engineering, and it contrasts only hands-on and simulated versions against a control where no practical component is used. The conflation of interface and mode is still present however – it is in fact explicitly referred to in this paper as 'physicality', which the virtual mode is said to lack. Coming from the science domain, it exists in a different citation structure than the engineering papers; however, the general tendency to presume the interdependence of interface and mode is retained. The paper found both hands-on and simulated supertype experiments yielded a significant increase in knowledge-based test performance over the control group which did not run experiments, but with no significant difference between themselves.

This paper applies rigorous cognitive theory to its design, and correctly identifies potential confounding elements from the wider cognitive system such as prior experience, difference in the nature of different experiments, etc. However, it falls into the same supertype conflation from the opposite direction – by failing to take into account the difference in data source that characterises the idea of laboratory technology. The most critical question left unanswered in the study is therefore: 'what if the benefit of 1 type of laboratory technology is equal to the benefit of the diagonally opposed interface?'. That is, the results for the proximal mode, haptic interface laboratory were similarly beneficial to the results for the simulated mode, computer mediated interface laboratory. However, the benefit in this context may be derived from the mode in the first case, and the interface in the second, mirroring the other – and a proximal mode, computer mediated interface laboratory may yield better results than either of the original versions. Without investigating the factors independently, this is impossible to determine either way.

IV. Motivations for Investigating Interfaces

If the path of least resistance yields the supertype conflation, what is the motivation for investing the effort to distinguish between the subcomponents? The key lies in isolating the reasons for the different learning (or other) outcomes that might be associated with each of the three supertypes, such that shortfalls in one or another may be alleviated, and benefits explicitly extracted.

Consider an empirical study investigating differences in outcomes between a hands-on supertype implementation of an experiment vs a remote supertype version. The hands-on experiment uses a haptic interface, is a proximal mode laboratory, and the user perceives it to be real and hands-on. The remote version uses a computer mediated interface, is a remote mode laboratory, and the user perceives it to be remote access to real equipment. If the study yields significant results in favour of one or another type, the naïve conclusion might be that 'hands-on laboratories perform better than remote laboratories', or vice versa. This however does not properly investigate the reason for the different outcomes, specifically whether they are caused by variations in the experiment interface, the lab technology, or the lab frame. If we could extract out these variables and examine them as independent, we could gain far more practical insights than if we ignore them. The key motivator is in the implications of the research – for example, if it were determined that the specific computer mediated interface is a cause of less desired outcomes (rather than, say, the remoteness of the experiment), this suggests interface innovations are a more relevant future research direction, such as virtual or augmented reality options. The only way to identify this is to distinguish each metric in the study.

Thus, the critical impact of this idea of interfaces is in analysing the results of comparative experiments such as those introduced in the case study papers, and specifically the idea of what it is they are actually comparing. A paper may present comparisons from the claimed case such as 'proximal laboratory vs remote laboratory' – when in fact they are comparing 'proximal laboratory with this specific haptic interface vs remote laboratory with this specific computer-mediated interface'. Which is not to say that such research is without merit, rather it means the question the research claims to be investigating may not be the question to which the data relates.

Furthermore, this paper does not seek to claim interface is entirely independent of laboratory mode. There is a cost and effort impact to distinguishing different design metrics which may be inherent to particular modes – this being the reason for the conflation in the first instance. It is also true that, barring very simple or very convenient cases, it would be quite impossible to generate a perfectly identical interface between any two laboratories – when one understands that interface encompasses more than simple questions of what a user sees and changes on a screen [14]. What remains important is to ensure only those attributes or parts of attributes which are truly tied to the choice of mode are considered an inherent part of that mode. To what extent any interdependence is allowed to influence the experiment design must lie with the intended research question - for example, the cost of implementing a haptic interface to a simulation has no bearing on a research question solely focused on learning outcomes but would have meaning in research investigating the cost efficiency in delivering those outcomes.

The selected papers explored above involve comparing one supertype of laboratory to another, where all or most of the contributing elements change between types. The direction of the above discussion is to motivate such research to consider a factorial approach, testing various combinations of interfaces and modes to see how these variables interact. However, it may also be applied in the case of a single mode. When investigating a single implementation of a laboratory, it highlights some ways to modify the implementation for comparison, to see what may improve its performance to some desired outcomes and in some particular contexts. This style of research is particularly suited to non-traditional laboratories, as the computer-mediated interface inherently enables all the HCI advances of recent history. Rich audio-visual media, haptic controls, augmented and virtual reality; all these interface choices combine with more mundane decisions such as text input or mouse control to yield interesting research directions for new and existing laboratories.

This idea of interface richness may be used to reinforce the overall idea that interface is important. It should be immediately obvious that a student will experience learning differently via a text-based terminal console than via a modern 3-dimensional audiovisual interface – whether for better or worse is not so obvious, and may differ depending on the context to which it is applied. It would be naïve to think that interfaces developed another 50 years hence could not provide a similarly different learning experience. Researchers should therefore be careful to avoid making generalizations which embed technological assumptions which we know to be variable over time.

A. Research Design

Differentiating laboratory interfaces typically requires some investment of time and cost (e.g. adding a computer interface to a proximal laboratory, or adding a haptic interface to a simulation). Furthermore, researchers have a vested interest in the time and cost efficiency of their research. It would therefore be beneficial to examine what methods may be used to direct interface distinction efforts to those instances where they would have the most impact.

As previously mentioned, those research papers which do allow the supertype conflation to occur are not without merit. In the case where a difference has been identified between two types of laboratory, the question should then turn to whether it is the mode or the interface (or both) which is the cause of the difference. There exist three possibilities to investigate this, based on the scenario AX > BY, where A and B are modes, X and Y are interface types or designs, and the ">" relationship relates to an improvement in some outcome (typically learning improvement):

- AX vs AY **or** BX vs BY : hold the mode constant,
- AX vs BX **or** AY vs BY : hold the interface constant, or
- AX vs AY vs BX vs BY : factorial study comparing all 4 possibilities simultaneously

Obviously, the most rigorous option is the third – knowing that we may not validly extrapolate results from a single variable of study across another, this is the only option which gives us total information. However, it is also the most expensive in time and cost to implement, and requires an exponential increase in sample size. Instead, we may use a single variable study to detect whether we are looking in the right place. If we know AX > BY based on our prior study, and we test AX vs AY:

- AX > AY : The interface has some contributing influence on the initial results,
- AX < AY : The interface has some limiting influence on the initial results, or
- AX ≈ AY : The mode has some contributing influence on the initial results – an AX vs BX or AY vs BY study may prove useful.

With similar result sets for the other testing methods. Each outcome provides some insight into what is occurring in the initial study, though it is not complete and may not be extrapolated - for example an insignificant result for AX vs AY does not imply the interface has no significant influence, just that it has no significant influence as applied to A. It may have an influence as applied to B, such that AX ≈ AY, but AX ≈ AY ≈ BX, and BX > BY.

Even with only partial knowledge however, we still gain insights into where research should look next. If we determine that interface has an impact on some proximal laboratory which did better against some remote version, we are then motivated to investigate ways to change the interface of the remote laboratory to improve its outcomes. If we determine students have better outcomes from real equipment than a simulation even though both used the simulation interface, this would promote the development of remote laboratories, rather than the development of improved simulation interfaces.

The choice of variables to examine must necessarily be informed by the time, cost, or indeed feasibility of the distinction. Certain study designs will be easier to implement than others, and it is finding the simplest variables to manipulate that gives this experimental design strategy its overall advantage. It would likely be far cheaper and easier to place an existing hands-on laboratory behind a computer interface than it would be to create and distribute a haptic interface to a simulation, for example. For some laboratories, it may not be possible with current technology to replicate an interface to the same level of media richness.

V. Conclusion

The conflation of partially independent input variables in modern laboratory experiment design is limiting the interpretation of current research and obscuring potentially beneficial new avenues of investigation. In this paper we have seen how proximal-haptic, remote-mediated, and simulated-mediated conflations have become prominent in the literature as 'supertypes', with research assuming that the pairings reflect inherent dependence, leaving the true causes of their results indeterminate. We have also discussed the theoretical reasons for these impacts and shown how they present in highly regarded research in this field. Finally, we have discussed paths that researchers may take in order to identify particular comparisons which may benefit from fully factorial research, or motivate research into more difficult or costly adaptations.

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