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Virtual and Physical Experimentation in Inquiry-Based Science Labs: Attitudes, Performance and Access

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Abstract This study investigated the learning dimensions that occur in physical and virtual inquiry-based lab investigations, in first-year secondary chemistry classes. This study took place over a 2 year period and utilized an experimental crossover design which consisted of two separate trials of laboratory investigation. Assessment data and attitudinal data were gathered and analyzed to measure the instructional value of physical and virtual lab experiences in terms of student performance and attitudes. Test statistics were conducted for differences of means for assessment data. Student attitudes towards virtual experiences in comparison to physical lab experiences were measured using a newly created Virtual and Physical Experimentation Questionnaire (VPEQ). VPEQ was specifically developed for this study, and included new scales of Usefulness of Lab, and Equipment Usability which measured attitudinal dimensions in virtual and physical lab experiences. A factor analysis was conducted for questionnaire data, and reliability of the scales and internal consistency of items within scales were calculated. The new scales were statistically valid and reliable. The instructional value of physical and virtual lab experiences was comparable in terms of student performance. Students showed preference towards the virtual medium in their lab experiences. Students showed positive attitudes towards physical and virtual experiences, and demonstrated a preference towards inquiry-based experiences, physical or virtual. Students found virtual experiences to have higher equipment usability as well as a higher degree of open-endedness. In regards to student access to inquiry-based lab experiences, virtual and online alternatives were viewed favorably by students.

Keywords Virtual labs · Inquiry-learning · Experimentation · Hands-on · Simulations · Chemistry

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Introduction

It has been widely established in the science teaching community that contemporary science environments should foster "hands-on", inquiry-based experiences and investigations that promote conceptual change (NSTA 2007; NRC 2006). These investigations should take place in the laboratory, the classroom, or the field where students are given opportunities to interact directly with naturally occurring phenomena or with data originating from such phenomena (NSTA 2007). The laboratory environment, in this regard, has been largely utilized as a *physical* space, with *physical* materials and equipment with which students interact. *Hands-on* has therefore implied: physicality (Zacharia 2007), 'real' experimentation (Klahr et al. 2007; Zacharia et al. 2008; Kirschner and Huisman 1998), and 'real' conceptual change (Akpan and Strayer 2010). Such settings can promote application of important authentic scientific processes (Akpan 2001; Akpan and Strayer 2010; NSTA 2007; NRC 2006). They can increase engagement and motivation through the kinesthetic manipulation of physical equipment and materials. They facilitate concrete-to-abstract conceptualization (Flick 1993), and can assist students in making real-world connections (NRC 2006; NSTA 2007). Conversely, arguments have been made that physical lab experiences may not always promote conceptual change. For instance, physical lab experiences may simply validate existing theory in fool-proof settings (Lagowski 2002); and may prevent students from identifying and altering misconceptions. This can hinder cognitive conflict and conceptual change (Kirschner and Huisman 1998; Nakhleh 1994; Eylon and Linn 1988). Students may become frustrated with the operation and manipulation of physical equipment (Pyatt and Sims 2007), and may focus instead on insignificant aspects of an underlying model (Finkelstein et al. 2005a).

Approaches to experimentation that center on physical equipment, physical material and physical facilities (Stone 2007; Lagowski 2002; Klahr et al. 2007), may be cost prohibitive (Huppert et al. 2002), and may consequently limit access (Stone 2007). For instance, recent court rulings have compelled school districts and teachers to provide students with alternatives to physical "hands-on" experimentation. Specifically, the "Dissection Alternatives Act" of (2000) compelled teachers to provide simulated alternatives to frog dissection. Similarly, in the "Demonstration of Restructuring in Publication Act" of (2000), school districts were compelled to provide students with online opportunities to Advanced Placement Science Courses and Labs. These rulings have set a precedent for instructional practice in lab settings. As a result, arguments have been made that hands-on can, and should also be *virtual*. In these cases, hands-on is more than just *physicality*, but rather *manipulation and experimentation* (Zacharia 2007; Marshall and Young 2006). It has been argued that virtual experimentation, too, can result in 'real' conceptual change (Jaakkola et al. 2010; de Jong and van Joolingen 1998; Zacharia 2007, 2005; Bell and Trundle 2008; Hsu 2008; Barnea and Dori 1999; Williamson and Abraham 1995). And the extent to which 'real' conceptual change occurs in hands-on settings (physical or virtual) depends heavily on: (a) type of instruction (direct or discovery), (b) type of knowledge to be acquired (domain-general or domain-specific) and (c) type of materials that are used (physical or virtual) (Klahr et al. 2007; de Jong 2006).

Much work has been done to understand how conceptual change occurs in inquiry-based hands-on environments, and what interplay exists between physical and virtual experimentation (Barnea and Dori 1999; Dori and Barak 2001; Jaakkola et al. 2010; Zacharia 2007; Finkelstein et al. 2005b; Akpan and Strayer 2010; Bayraktar 2002; Huppert et al. 2002; Winn et al. 2006; Bell and Trundle 2008; Williamson and Abraham 1995; Rivers and Vockell 1987). The bulk of this work has studied: (1) virtual experimentation versus physical experimentation with explicit instruction (structured inquiry); (2) virtual experimentation and physical experimentation with explicit instruction; (3) virtual experimentation versus physical experimentation with implicit instruction (open inquiry); (4) virtual experimentation and physical experimentation with implicit instruction. The findings suggest that, in terms of impacting conceptual change in science environments, virtual experimentation, when compared to physical experimentation, may yield equal if not greater gains (Zacharia 2007; Finkelstein et al. 2005a; Jaakkola et al. 2010; Akpan and Strayer 2010; Bayraktar 2002; Huppert et al. 2002; Winn et al. 2006; Bell and Trundle 2008; Pyatt and Sims 2007; Baxter 1995; Kumar and Sherwood 2007; Barnea and Dori 1999; Rivers and Vockell 1987). This is partly because the formation of procedural and conceptual knowledge may not require physical interaction with materials; and substituting virtual experimentation for physical may have no negative effect (Zacharia et al. 2008). For instance, even though virtual experimentation may not provide an authentic field-based experience, it can provide an authentic model-based experience (Winn et al. 2006). The instructional medium (physical or virtual), may have little or no effect on the learner's ability to describe causal relationships in inquiry settings (Klahr et al. 2007). What does significantly impact students' ability to form conceptual change in inquiry-based lab environments are student attitudes towards a given instructional medium and instructional approach (Winn et al. 2006; Bayraktar 2002; Zacharia 2003; Bhargava et al. 2006; Kumar and Sherwood 2007). For instance, student attitudes towards virtual experimentation or physical experimentation can impact overall learning gains in such settings. Further, student attitudes towards inquiry-based learning can also have significant impact on student's ability to form conceptual change. Hands-on inquiry-based instruction is a widely accepted instructional approach used for science teaching and learning (NRC 2006; NSTA 2007; Lagowski 2002), even though there exist several interpretations of what constitutes inquiry-based instruction (de Jong and van Joolingen 1998; Wieman et al. 2008; Jaakkola and Nurmi 2008; Bell and Trundle 2008; Klahr et al. 2007; Dewey 1938). And there are several interpretations regarding the effectiveness of the inquiry-based approach and how it should be implemented, regardless of how "hands-on" is defined (Jaakkola et al. 2010). For instance, inquiry-based learning can be difficult to implement (de Jong and van Joolingen 1998), and may not always yield positive learning gains (Klahr and Nigam 2004).

In such settings, the learner is an active agent in the process of knowledge acquisition (de Jong and van Joolingen 1998). And may therefore need support in overcoming misconceptions when learning the scientific model under investigation (Finkelstein et al. 2005a; Frederiksen et al. 1999; Jaakkola and Nurmi 2008). For instance, students need support in designing experiments which promote cognitive conflict—accurately interpreting the results of manipulated variables—along with how to modify experimental design to further understand naturally occurring and complex phenomena (de Jong and van Joolingen 1998; Hsu 2008; Huppert et al. 2002; Stone 2007). They need support in overcoming confirmation bias– the tendency to confirm rather than disconfirm hypotheses (de Jong and van Joolingen 1998). Approaches such as structured-inquiry (e.g., guided discovery) (de Jong and van Joolingen 1998) have been therefore proposed as alternatives which can provide needed support and yield positive learning gains. It has also been shown that technology-enhanced inquiry instruction, like animations and simulations can provide learners with necessary support (Hsu 2008; Stone 2007; Bell and Trundle 2008; Derting and Cox 2008). Simulated lab experiences can provide students with virtual and concrete representations of naturally occurring phenomena. This can reduce cognitive load, and promote conceptual change (Jaakkola et al. 2010; Triona and Klahr 2003; de Jong and van Joolingen 1998). Simulations can promote inquiry instruction through a self-paced, learn-by-doing approach (Akpan and Strayer 2010; Bell and Trundle 2008; Stone 2007), and can facilitate conceptual change (Tao and Gunstone 1999). They can promote realism, exploration and multiple representations of naturally occurring phenomena which can provide learners with needed visualization for conceptual understanding (Hsu 2008; Zacharia 2005; Kumar and Sherwood 2007; Williamson and Abraham 1995; Burkholder et al. 2008; Clariana 1989). They can be effective alternatives for laboratory experiments when the experimental apparatus is too complex, dangerous, expensive, or inaccessible; or when the experimental procedure is too time consuming (Moore and Thomas 1983; Stone 2007). Recent evidence also suggests that when virtual experimentation is used, concurrently or subsequent to physical experimentation, the learning gains are equal if not greater (Zacharia 2007; Akpan and Strayer 2010; Jaakkola et al. 2010; Tao and Gunstone 1999; Triona and Klahr 2003; Zacharia et al. 2008; Dori and Barak 2001; Baxter 1995). They have the potential to promote access through the creation of least restrictive environments for experimentation (Kinzie et al. 1993), and have therefore been proposed as viable alternatives to conventional experimentation (Akpan and Strayer 2010; Pyatt and Sims 2007; Dissection Alternatives Act 2000).

Therefore, in regard to conceptual change, there have been a number of studies which have shown that virtual hands-on experiences can attain learning goals much like physical hands-on experiences have. It appears that conceptual change may be possible in both virtual and physical settings (Triona and Klahr 2003; Zacharia et al. 2008). Although, the adoption of virtual hands-on experiences has thus far been met with great resistance (Pyatt 2009). For example, virtual experimentation is currently viewed as an enhancement to, but not replacement for hands-on (physical) experimentation (NSTA 2007). Given the potential of virtual or simulated approaches to meet or exceed the learning outcomes of conventional lab approaches, simulations are the least used technology applications in education (Akilli 2009; Pyatt and Sims 2007; Dissection Alternatives Act 2000; Demonstration of Restructuring in Public Education 2000).

From this review, it is apparent there may be more than one effective approach to hands-on experimentation in inquiry-based instruction. There is evidence that students can form conceptual change in both inquiry-based virtual and physical experiences. The design of contemporary hands-on inquiry is not exclusively about one approach versus another (e.g., physical versus virtual, explicit versus implicit), but rather about alternatives and options for students, and how to best support students' conceptual change in such settings. And that the instructional medium, instructional approach and learner attitudes matter a great deal in whether or not conceptual change occurs. Access to contemporary hands-on science instruction (physical or virtual) is a critical component of effective laboratory design (Nakhleh 1994). It is therefore necessary, when designing contemporary inquiry-based science instruction, to consider issues of access and alternative approaches to hands-on experimentation (physical, virtual or some combination). It is also important to gauge learners' attitudes towards the instructional medium and instructional approach used. These approaches should: (1) be developmentally appropriate for students of all ages and ability levels (NSTA 2007; Nakhleh 1994); (2) facilitate conceptual change and cognitive conflict (Bell and Trundle 2008; Jaakkola et al. 2010; Zacharia 2007; Hsu 2008); and (3) promote access for all students (NSTA 2007; Dissection Alternatives Act 2000; Demonstration of Restructuring in Public Education 2000; Nakhleh 1994).

Objectives

This study investigated how hands-on experimentation (physical and virtual) can be effectively used in an inquiry-based science environment to promote conceptual change and access. The research questions investigated here are:

1. What is the instructional value of physical and virtual experimentation in terms of student performance?
2. What is the instructional value of physical and virtual experimentation in terms of student attitude?
3. How can inquiry-based lab instruction be designed to promote access to inquiry-based lab experiences.

Methods

This study looked at the learning dimensions that occur in physical and virtual hands-on inquiry-based lab investigations, in first-year secondary chemistry classes. It has been shown that in these settings, students should encounter complexity and ambiguity of empirical work (NRC 2006), and should develop skills in interpreting and analyzing their observations. It has further been shown that such settings should promote sharing tasks, contributing and responding to ideas (NRC 2006; NSTA 2007). There have been many peer-reviewed laboratory experiences which have been designed to address these goals (Demmin et al. 2010; NSTA 2007). The lab investigations chosen for this study were recommended laboratory investigations for students in preparation of advanced placement chemistry (Demmin et al. 2010), and were previously adopted and integrated into the existing chemistry curriculum where the study took place. These investigations focused on the topic of stoichiometry, which has been shown to be a particularly significant and challenging concept for students (Jensen 2003); and one which hands-on experimentation can facilitate the formation of conceptual understanding (College Board 2010).

Design

This study utilized an experimental crossover design (Kenward 2005) which consisted of two separate trials of laboratory investigation: trial-1 *Empirical Formula of a Hydrate*; trial-2 *Stoichiometry by Loss of* CO_2. The crossover design was chosen because it allowed comparisons between control and treatment groups for each trial, while at the same time allowed each participant to experience two different independent lab experiences. This allowed for a within-subject attitudinal comparison of physical and virtual lab experiences. This also allowed for comparisons of performance and attitude for each participant. The crossover design was appropriate because many similar studies have exposed learners to one or the other—physical experimentation or virtual experimentation—but not both. The crossover design used in this study allowed for both.

Each of the two trials used in this study consisted of a treatment (virtual lab experience) and control (physical lab experience) for a lab investigation involving chemical stoichiometry. The laboratory procedures, background material, and required materials and equipment were identical for the control and experimental group. The only difference was that the control group ran the laboratory investigation using actual equipment and materials, while the experimental group ran the laboratory investigation using only laptop computers. The computers had a simulation of the same lab. The simulation software selected for this study was from (Late Nite Labs 2008). This software has been widely used in college-level and high-school level chemistry courses, and includes a suite of laboratory experiences consistent with those recommend for preparation of advanced placement chemistry (Demmin et al. 2010). Student performance (cognitive domain) for each laboratory investigation was measured as were student attitudes (affective domain) towards the virtual and physical laboratory investigations. This approach was similar to other studies which have gathered comparative data to answer questions in the cognitive and affective domain (Dori and Barak 2001; Jaakkola et al. 2010; Zacharia 2007; Finkelstein et al. 2005a; Akpan and Strayer 2010; Bayraktar 2002; Huppert et al. 2002; Winn et al. 2006; Bell and Trundle 2008; Bourque and Carlson 1987; Kennepohl 2001; Stieff and Wilensky 2003).

Variables

Dependent Variable

Lab performance was the dependent variable identified in this study. Lab performance measured students' ability to effectively follow prescribed laboratory procedures in the set-up, and manipulation of necessary laboratory equipment and materials so that accurate data could be generated. Laboratory performance also measured students' ability to interpret collected data and formulate hypotheses, and conceptual models based on the data that were gathered. Lastly, laboratory performance measured students' ability to utilize their conceptual models in making predictions in the domain of chemical stoichiometry.

Independent Variables

The independent variables identified in this study were the laboratory materials and equipment which were encountered in the virtual and physical laboratory settings for trial-1 and trial-2. While this study assumed that materials and equipment were the same for physical and virtual experiences—usability of materials and equipment—the design of this study cannot guarantee that this was the case. This was a fair assumption, given that the instructional medium (physical or virtual) should have little or no effect on the learner's ability to describe causal relationships in inquiry settings (Klahr et al. 2007). Further, any differences existing between the physical and virtual equipment and materials were also accounted for in the attitudinal comparisons where students evaluated the perceived differences between virtual and physical experimentation. This is an appropriate assumption, given that one of the goals of this study was to measure differences in the affective domain between virtual and physical experimentation.

Sample

This study took place in a public suburban high-school in southwestern USA. The duration of the study was a 2 year period and involved a total of 8 first-year chemistry classes ($N = 184$): 4 classes participated in year one ($N = 96$); and 4 participated in year two ($N = 88$). The same instructor taught all 8 of these classes. One of the authors of this study was also the instructor of record where the study took place. This study strictly adhered to IRB protocols. An IRB approval was obtained before the study began.

Pilot Test

Prior to running the study, a pilot test was carried out. This was conducted to measure fidelity of experimentation—that data generated via virtual equipment and physical equipment—were the same for both laboratory investigations (virtual and physical) for each trial. The pilot study was conducted with a practice run of the experiment using the requisite equipment and materials in conjunction with the performance assessments and the student survey. This included making sure technical aspects, like computers, internet access, student login, etc., worked as intended. The pilot study allowed researchers to ensure that data generated for each laboratory investigation (virtual and physical) was congruent, and that the resulting analyses, hypotheses, and conceptual models for the chemical stoichiometry domain were congruent. The pilot test involved carrying out trials 1 and 2, as described below, with a group of chemistry students who did not participate in the final study.

Training Session

Each of the chemistry classes participating in the study underwent a 20 min computer-training session. In this training, participants were introduced to the simulation software, and went through an online tutorial which trained them in the use of the virtual equipment found in the LateNite Labs simulation. The training was solely focused on providing familiarity with virtual experimentation and did not provide information regarding chemistry concepts. This training occurred at a separate time and prior to the beginning of the study. There was no training on the physical equipment during this training, as students received training on the physical equipment prior to this study.

Trial-1

Participants were randomly assigned participants to either a control (physical lab investigation) or treatment group (virtual lab investigation) for the trial-1 laboratory investigation. Trial-1 was then carried out by participants in each class. The class periods were approximately 55 min. Following the trial-1 lab investigation, participants completed a lab assessment which measured student performance (cognitive domain). It required students to analyze, interpret and formulate hypotheses from data collected throughout their lab experience—virtual or physical. The assessment was the same for the control and for the treatment groups.

Trial-2

Approximately 1 week later, participants who were assigned to the control group for trial-1, crossed-over to the treatment group for trial-2. Similarly, trial-1 participants who were assigned to the treatment group, crossed-over to the control group for trial-2. The trial-2 laboratory investigation was then carried out by students in each of the participating classes. The class periods were 55 min. Following the trial-2 laboratory investigation, participants completed a lab assessment which measured student performance (cognitive domain) and required students to analyze, interpret and formulate hypotheses from data collected—virtual or physical. Following the completion of the trial-2 assessment, participants completed a survey which measured student attitudes towards the virtual and physical lab experiences for the trail-1 and trial-2 laboratory investigations.

Survey Development

As was identified in the literature review, several factors can influence students' performance and attitudes in virtual and physical lab investigations. For instance, students' attitudes towards the instructional medium and instructional approach can influence students' ability to form conceptual change in science lab environments (Winn et al. 2006; Bayraktar 2002; Zacharia 2003; Bhargava et al. 2006). Therefore a survey was designed for this study to measure learner attitudes towards virtual and physical lab experiences. This survey was based on: (1) The Science Laboratory Environment Inventory (SLEI) (Fraser et al. 1993a; Aladejana and Aderibigbe 2007), which identified scales for *student cohesiveness*, *open-endedness*, *integration*, *rule clarity*, and *material environment*; (2) The Computer Laboratory Environment Inventory (CLEI) (Newby and Fisher 1997), and Attitudes towards Computers and Computer Courses (ACC) (Woodrow 1994), which had scales of: *anxiety towards computers*; *enjoyment of computers*; *usefulness of computers*; and *usefulness of course*. All of these scales measured experiences in either physical laboratory environments or computer laboratory environments, but not both. For this study, it was also important to capture information regarding students' perceptions towards virtual lab experiences in comparison to

Table 1 Description of scales used in the virtual and physical experimentation questionnaire (VPEQ)

Scale	Description	Sample item
Usefulness of computers[a]	Extent to which the students believe computers are useful.	I enjoy learning on a computer (+)
Anxiety towards computers[a]	Extent to which student feels comfortable using computer.	Working with computers makes me nervous (−)
Usefulness of lab[c]	Extent to which student feels labs are useful.	I like the regular lab (+)
Open-endedness of lab[b] (virtual/physical)	Extent to which the laboratory activities emphasize an open-ended, divergent approach to experimentation.	It is easier to experiment and explore in virtual labs than in regular labs (+)
Equipment usability[c] (virtual/physical)	Extent to which students can operate lab equipment.	The regular labs were easier to learn and operate than the computer equipment (−)

[a] ACC, [b] SLEI, [c] New scale. Items designated (+) are scored 1,2,3,4 and 5, respectively, for responses almost never, Seldom, Sometimes, Often, Very Often. Items designated (−) are scored 5,4,3,2 and 1, respectively for responses Very Often, Often, Sometimes, Seldom, Almost Never

physical lab experiences. Therefore, two more scales were created for this study: (1) Usefulness of Lab (virtual/physical); and (2) Equipment Usability (virtual/physical) (Table 1). Further, the scale of open-endedness (Fraser et al. 1993b), was also modified for this study to measure attitudes in both virtual and physical lab experiences. The survey created for this study, *the Virtual and Physical Experimentation Questionnaire (VPEQ)*, was comprised of 39-items in a Likert-scale form (Online Resource 1). The five response alternatives for each item were Very Often, Often, Sometimes, Seldom, and Almost Never. Details about validation procedures are described in the results section below.

Data Analysis

Assessment data and attitudinal data were then gathered and analyzed. Test statistics were carried out to determine differences of means for the assessment data from trial-1 and trial-2. A factor analysis was then conducted for the survey data that were gathered for student attitudes. The reliability of the scales and internal consistency of items within the scales were also calculated. The results of which are presented in the following section.

Results

This study gathered data on learner performance and learner attitude from virtual and physical lab environments. Learner performance was measured for the virtual and physical lab experiences for both trials and is presented below. Learner attitude towards each environment was measured on the survey administered upon completion of trial-2. These are also presented in the following section.

Performance Data

Trial-1

A total of ($N = 184$) students completed the trial-1 laboratory experience: *Empirical Formula of a Hydrate.* Ninety-eight students were assigned to the control group and 86 were assigned to the treatment group. Student performance on the laboratory assessment which was given at the end of the laboratory investigation is reported in Table 2. Student assessments were then evaluated. Students received either 1 point or zero points for this assessment. Each student completed the lab assessment. The same lab assessment was used for the control group and for the treatment group. The mean lab performance score for the control group was ($M = .49$, SD $= .50$) and the mean lab performance score for the treatment group was ($M = .64$, SD $= .48$). A *t* Test was conducted for this sample to determine whether or not significant differences existed between the mean performance scores for the control and treatment group. Based on the *t* Test, $t(1) = 1.71$, ($p < .09$), we failed to reject the null hypothesis: H_o: $M_{control} = M_{treatment}$, and reject the alternate: H_1: $M_{control} \neq M_{treatment}$. These findings show that there was no significant difference between mean assessment scores for the control (physical lab) group and for the treatment (virtual lab) group. Students who conducted the trial-1 lab virtual investigation scored the same as students who performed the identical lab using physical equipment and materials. There were no significant differences between mean assessment scores for virtual lab and physical lab groups.

Trial-2

A total of ($N = 184$) students conducted the trial-2 laboratory experience: *Stoichiometry by Loss of* CO_2. Eighty-six students were assigned to the control group and

Table 2 Performance data for trial-1 and trial-2 post-lab assessments

Variable	Trial-1 empirical formula of a hydrate				Trial-2 stoichiometry by loss of CO_2			
	Control		Treatment		Control		Treatment	
	M	SD	M	SD	M	SD	M	SD
Lab performance	.49	.50	.64	.48	.068	.25	1.2	1.3
%	49%		64%		2.2%		40%	

Alpha = .05

($N = 98$) were assigned to the treatment group. Student performance on the laboratory assessment is reported in Table 2. Student assessments were then scored. Students received 3, 2, 1, or zero points for this assessment. The same lab assessment was used for the control group and for the treatment group. The mean lab performance score for the control group was ($M = .068$, SD = .25) and the mean lab performance score for the treatment group was ($M = 1.2$, SD = 1.3). A t Test was conducted for this sample to determine whether or not significant differences existed between the mean performance scores for the control and treatment group. Based on the t Test, $t(1) = 6.50$, ($p < .0001$), we rejected the null hypothesis: H_o: $M_{control} = M_{treatment}$; and accepted the alternate: H_1: $M_{control} \neq M_{treatment}$. These findings show that the mean assessment scores for the control (physical lab) group were significantly lower than the mean assessment scores for the treatment (virtual lab) group. Students who conducted the virtual version of the tial-2 lab investigation significantly outperformed students who performed the same lab using physical equipment and materials. It should also be pointed out in this analysis, that the standard deviation for assessment data was relatively high in that they approached, and in some cases, exceeded (e.g., $M = .068$, SD = .25) the mean. Possible reasons for this error are described further in the discussion.

Attitudinal Data

Reliability and Factorial Validity of Questionnaire

A total of ($N = 173$) students completed the Virtual and Physical Experimentation Questionnaire (VPEQ) which measured learner attitudes towards experimentation in virtual and physical environments. The survey data were gathered and analyzed with the statistical analysis package SPSS. A dimension reduction procedure (Principal Components Analysis) was executed on all 39 survey items, and coefficients less than .4 were suppressed. A resulting component matrix was produced (Online Resource "Component matrix"). Three survey items, 1, 7, 17, had coefficients less than .4, and were omitted from the data set. After the preliminary analysis, the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy was performed to determine whether or not sampling diffusion was present. The KMO was determined to be .868, which indicated high confidence in selecting factor analysis as an appropriate method for analyzing the survey data. An analysis of the Eigen values and scree plot revealed that there was most likely a 4 or 5-factor solution for the data set. Factor loadings were then carried out on the data set. Some items loaded heavily on more than one factor, and several items had low factor loadings within identified scales. Therefore, items 2, 4, 7, 35, 38 and 39 were omitted from the final factor solution. The resultant factor loadings are listed below for the 29 items which were described by a 5-factor solution (Table 3). The new scales used in this study, Usefulness of Lab, and Equipment Usability, had factor loadings ranging from .457 to .857. Once factor loadings were completed, measures of internal consistency for each scale were carried out. Cronbach's Alpha for scale reliability was calculated for each of the 5 scales. The range for theses values was from .723 to .904. Measures of internal consistency for the two new scales were .723 and .796, respectively. All factor loadings were above .4, and all alpha scales were above .70. Based on this analysis, the 5-factor solution describing student attitudes and perceptions towards physical and virtual lab experiences was a statistically reasonable solution and predictor of the dimensions measured by the scales. The final mean and standard deviation calculated for each of the five scales and are reported in Table 4.

Description of the Factors

Student attitudes towards virtual and physical experimentation were measured using the Virtual and Physical Experimentation Questionnaire (VPEQ). This survey measured five scales which were specific to learning dimensions which have been reported to have significant impact on student's success in experimental settings. The averages for each scale are presented in Table 4. Two of the scales used in this study measured environmental aspects of the experimental settings, and did not measure comparisons between physical and virtual lab experiences. Rather, they measured student attitudes towards computers. These scales were: (1) usefulness of computers (e.g.,

Table 3 Factor loadings and alpha reliabilities for usefulness of computers (UC), anxiety towards computers (AC), equipment usability (virtual/physical) (EU), open-endedness of lab (virtual/physical) (OE), usefulness of lab (UL)

Factor loading					
Item no	Usefulness of computers	Anxiety towards computers	Equipment usability (virtual/physical)	Open-endedness of lab (virtual/physical)	Usefulness of lab
6	.694				
9	.795				
16	.825				
18	.890				
19	.804				
25	.728				
28	.834				
5		.779			
13		.865			
14		.766			
32		.648			
11			.510		
12			.857		
20			.836		
27			.517		
29			.857		
36			.778		
15				.718	
22				.717	
23				.784	
24				.806	
26				.811	
30				.778	
31				.770	
3					.656
8					.763
10					.797
33					.750
34					.457
Alpha reliability	.904	.764	.796	.885	.723

computer simulations allow me to study problems that are complex and realistic), and (2) anxiety towards computers (e.g., working with computers makes me nervous).

Use of New Scales

Because a major aspect of this study was to measure factors within the affective domain which may influence students' perceptions and attitudes towards efficacy of virtual and physical experimentation, and because previously validated instruments have measured solely dimensions in physical lab experiences, three new scales were created in this study to measure dimensions that occur in both physical and virtual lab experiences. These three scales were: (1) *open-endedness of lab* (e.g., there is opportunity for me to pursue my own experimental interests in virtual/physical lab), (2) *usability of lab equipment* (e.g., the regular labs were easier to use and operate than the computer equipment), and (3) *usefulness of lab* (e.g., lab experiments give me a better sense of problems likely to be encountered in "real" life). These scales measured factors which have been shown to significantly impact students' understanding of underlying scientific phenomena. The averages for each scale are presented in Table 4.

Table 4 Mean and standard deviation for virtual and physical lab environment scales measured with Virtual and Physical Experimentation Questionnaire (VPEQ)

Scale	No of items	Mean	Standard deviation
Usefulness of computers	7	3.7	1.1
Anxiety towards computers	4	1.8	1.0
Equipment usability	6		
Virtual		3.5	1.1
Physical		2.5	1.1
Open-endedness	7		
Virtual		3.7	1.2
Physical		2.3	1.2
Usefulness of lab	5		
Virtual		3.3	.086
Physical		3.2	.085

The equipment usability, usefulness of lab, and open-endedness of lab scales were comparative scales which measured student attitudes towards virtual and physical experimentation. It is noted here that while some elements of the open-endedness scale were adapted from (SLEI) (Fraser et al. 1993a), several items were modified to measure either virtual or physical aspects of lab open-endedness. The usefulness of computers and Anxiety towards computers scales were adapted from the computer laboratory environment inventory (*CLEI*) (Newby and Fisher 1997), and attitudes towards computers and computer courses (*ACC*) (Woodrow 1994). These scales measured both student attitudes and perceptions towards computer use in classroom and laboratory settings

Attitudes Towards Virtual and Physical Experimentation

Student attitudes towards virtual and physical lab environments were as follows. First, on the scale of *usefulness of computers*, students scored ($M = 3.7$, SD = 1.1). This indicates approximately (73%) of students agreed that computers were useful. Second, on the scale of *anxiety towards computers,* students scored ($M = 1.8$, SD = 1.0). This indicates that over (64%) of students had little or no anxiety towards the use of computers in classroom and laboratory settings. Third, regarding the *equipment usability* scale, students rated the physical lab as ($M = 2.5$, SD = 1.1). This means that (50%) of students found the physical lab equipment easy to use. Conversely, students rated the usability of virtual equipment as ($M = 3.5$, SD = 1.1). This indicates that (70%) of students felt that the virtual equipment was easy to use. Fourth, on the scale of *open-endedness of lab*, students rated their physical lab experience as ($M = 2.3$, SD = 1.2). Approximately (46%) of students viewed physical labs as being open-ended. Students rated their virtual lab experience as ($M = 3.7$, SD = 1.1), indicating that (74%) of students viewed virtual experiences as being open-ended. Fifth, on the scale of *usefulness of lab*, students rated the physical lab experience as ($M = 3.2$, SD = .086), indicating that (64%) of students perceived physical lab experiences as being useful in their

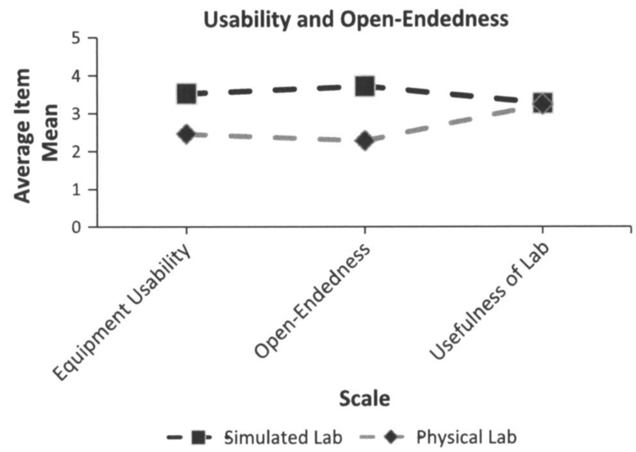

Fig. 1 Mean item equipment usability, open-endedness and usefulness of lab in physical and virtual lab experiences

learning. Students rated virtual lab experience as ($M = 3.3$, SD = .085). Sixty-five percent of students viewed virtual experiences as useful to their learning. Figure 1 displays student attitudes towards virtual and physical experimentation as measured by open-endedness, usability of lab equipment, and usefulness of lab for physical and virtual environments.

In summary, students demonstrated an above average comfort level with computer use in lab settings. Students found the virtual equipment easier to use than the physical equipment. They also found virtual experimentation more open-ended than physical experimentation. Students found the usefulness of virtual labs and physical labs to be similar, if not the same. Students generally found physical and virtual labs useful towards their learning, and expressed no significant preference towards one environment over the other.

Discussion

The goals of this study were to investigate the instructional value of physical and virtual lab experiences in terms of student performance and student attitudes; and to investigate how inquiry-based lab instruction should be designed to promote access to inquiry-based lab experiences.

What is the Instructional Value of Physical and Virtual Lab Experiences in Terms of Student Performance?

Regarding instructional value of physical and virtual lab experiences, in terms of student performance, this study found two things. On one hand, there was no difference in the degree to which either experience (physical or virtual) promoted conceptual change. Both experiences provided instructional value, and students performed equally well in either environment. For example, trial-1 data revealed there was no significant difference in learning outcomes between physical and virtual lab experiences. Mean assessment scores from the physical and virtual lab experiences for this trial were ($M = .49$, $SD = .50$) and ($M = .64$, $SD = .48$), respectively. These findings were consistent with similar studies which have found the formation of procedural and conceptual knowledge may not require physical interaction with materials, and that substituting virtual for physical experimentation may have no negative effect (Zacharia et al. 2008). Therefore this study found that, in terms of student performance, the instructional value of physical and virtual lab experiences was satisfactory. This indicates that the instructional medium may have little effect on overall learning gains (Klahr et al. 2007; Clark 1994). This study also found physical and virtual experiences can promote conceptual change and can aid students' understanding of naturally occurring phenomena.

On the other hand, based on the trial-2 investigation, virtual lab experiences resulted in higher learning gains than physical lab experiences. For example, there were significant differences in learning outcomes between physical and virtual experiences. Assessment means for physical and virtual experiences for the trail-2 investigation were ($M = .068$, $SD = .25$) and ($M = 1.2$, $SD = 1.3$). The virtual lab experience promoted greater conceptual change than the physical lab experience. These findings were consistent with other studies which have found virtual experimentation when compared to physical experimentation may yield equal if not greater gains (Zacharia 2007; Finkelstein et al. 2005a; Jaakkola et al. 2010; Akpan and Strayer 2010; Bayraktar 2002; Huppert et al. 2002; Winn et al. 2006; Bell and Trundle 2008; Pyatt and Sims 2007). One of the reasons for the differences in assessment means for trial-2 may be illustrated in the following figures of student assessment samples.

Notice the differences in data gathered for the physical version and virtual version of the trial-2 lab investigation, where students were to utilize data generated in the lab investigation, and plot the data on a graph (Figs. 2, 3). Students then analyzed the graph and identified the point of inflection on the graph which corresponded to a reaction coefficient. The student sample from the physical experience of trial-2 (Fig. 2) demonstrates a point of inflection occurring at .02 x-axis, and .02 y-axis. The point of inflection determined in the virtual lab (Fig. 3) occurred at .08 x-axis and .06 y-axis. This latter ratio from the virtual experience was the accurate representation of the underlying chemical phenomena, and was necessary to determine the correct reaction coefficients for the chemical species under investigation. This example illustrates a connection between equipment usability, and conceptual understanding. This study revealed that students, who accurately measured and gathered data describing a naturally occurring phenomenon, were more likely to describe an accurate model of the phenomena under investigation. Conversely, students who made errors in generating and gathering data, as might have been with improper equipment use (e.g., did not zero a balance, misread a graduated cylinder, did not calibrate a device correctly), and consequently used erroneous data as "inputs" for their

A	B	C	D	E	F	G
Beaker #	Mass Beaker + H_2SO_4 (20 mL)	g Na_2CO_3 added	g Beaker + H_2SO_4 + Na_2CO_3 (after reaction)	g CO_2 lost: (C - (D-B))	mol Na_2CO_3	mol CO_2 lost
1	23.663	1	20.597	3.066	.0114	.0697
2	23.623	2	24.749	1.116	.0187	.0254
3	20.491	4	22.599	1.989	.0454	.0446
4	17.160	12	25.910	8.798	.1363	.1999
5	26.403	6	23.915	3.512	.0681	.0798
6	18.332	8	23.187	4.855	.0900	.1103
7	21.296	16	37.375	6.082	.1156	.1582

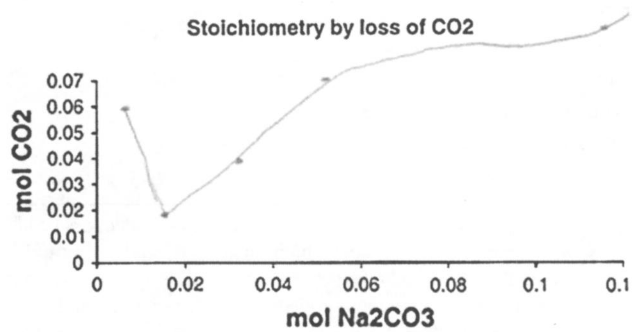

Fig. 2 Student data sample from *physical* version trial-2 investigation: "Stoichiometry by loss of CO_2"

A	B	C	D	E	F	G
Beaker #	Mass Beaker + H_2SO_4 (20 mL)	g Na_2CO_3 added	g Beaker + H_2SO_4 + Na_2CO_3 (after reaction)	g CO_2 lost: (C - (D-B))	mol Na_2CO_3	mol CO_2 lost
1	70.035	1	70.620	.415	.0094	.0094
2	70.035	2	71.205	.83	.01887	.01887
3	70.035	4	72.375	1.666	.0377	.0377
4	70.035	6	73.544	2.491	.0566	.0566
5	70.035	8	75.395	2.64	.0755	.060
6	70.035	10	77.395	2.64	.0943	.060
7	70.035	12	91.395	2.64	.1132	.060

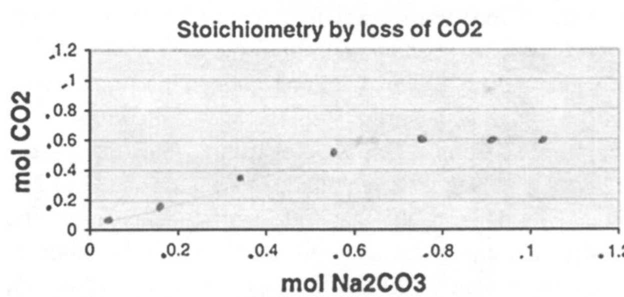

Fig. 3 Student data sample from *virtual* version trial-2 investigation: "Stoichiometry by loss of CO_2"

conceptual model, would erroneously describe the phenomenon under investigation. This illustrates that conceptual understanding is related to students' ability to effectively gather relevant information about a given phenomena, and effectively interpret these data to form a conceptual model. This also illustrates a sequential relationship. Regardless of students' skill in analyzing and interpreting data, the accuracy of the data gathered was a limiting factor in the students' overall conceptual understanding.

Therefore, this study found that virtual lab experiences resulted in greater learning gains above and beyond those achieved in comparable physical lab experiences. This indicates that, in terms of learning outcomes, virtual lab experiences were equal to, if not greater than physical lab experiences.

It should also be pointed out, however, that the standard deviation for assessment data was relatively high when compared to the assessment means. Possible reasons for high standard deviations may be related to the assessment design, or the fact that there was only one assessment provided after the lab experience was complete. It might be appropriate in future studies to have an assessment question with several subsequent parts. Also, it might be appropriate to have an assessment that measures several aspects of the laboratory experience. For example, it would be appropriate to have one or multiple assessments that: (1) measured students' ability to effectively design an experiment; (2) measured students' ability to effectively gather and collect data; (3) measured students' ability to analyze and interpret their results; and (4) measured students' ability to apply and integrate their interpretations and findings to explain the overarching phenomena or conceptual model under investigation.

What is the Instructional Value of Physical and Virtual Lab Experiences in Terms of Student Attitudes?

Because it has been shown that student attitudes towards a given instructional medium and instructional approach can influence the degree to which conceptual change occurs (Winn et al. 2006; Bayraktar 2002; Zacharia 2003; Bhargava et al. 2006), it was necessary to gauge students' attitudes towards computer use in lab settings. This was accomplished through measuring student attitudes on the scales *usefulness of computers*, and *anxiety towards computers*. Students' attitudes towards computer use in lab settings were favorable. Seventy-three percent of students believed that computers were useful in lab settings and (64%) had little or no anxiety towards the use of computers in laboratory settings. For example, (84%) of students sated they "enjoy learning on a computer", and (74%) of students stated that "I would like to see more computer-simulated experiments in the chemistry curriculum". Seventy-five percent of students agreed with the statement that "computer simulations are a good way to learn processes and concepts", and (71%) of students agreed with the statement "the computer simulations allowed me to study problems that are more complex and realistic than regular labs". These findings suggest that, in terms of an instructional medium for lab experiences, students showed preference towards the inclusion of computers in lab settings. Even though arguments have been made that the instructional medium, in and of itself, should not impact conceptual change (Klahr et al. 2007; Clark 1994), this study found that students viewed virtual lab experiences as realistic, complex and effective. This is consistent with the results of similar studies which have shown that virtual experiences are attractive when they save time, simplify experimental procedures (Moore and Thomas 1983; Stone 2007), promote realism and needed visualization, and assist in forming conceptual understanding (Foti and Ring 2008; Hsu 2008; Donovan and Nakhleh 2007; Zacharia 2005). Conversely, these findings contradict claims that virtual experiences are not authentic, not "real" (NRC 2006; NSTA 2007).

It has also been reported that students' ability to form conceptual change in inquiry-based lab settings is influenced by the level of support students are provided in understanding naturally occurring phenomena (de Jong and van Joolingen 1998; Hsu 2008; Huppert et al. 2002; Stone 2007). In this study, the scale *usefulness of lab* measured student attitudes towards how well the lab experience (physical or virtual) assisted them in forming conceptual change. There was no significant difference in student attitudes towards the usefulness of lab in promoting conceptual change. Sixty-four percent of students reported their physical lab experiences as being useful in learning chemical stoichiometry, and (65%) of students viewed virtual lab experiences as being useful to their learning. Virtual and physical experiences were viewed by students to have the same effect on their learning. Seventy percent of students agreed with the statement "I liked the regular lab", and (81%) agreed with the statement "I liked using the computer simulations". These findings were consistent with the literature. Students value inquiry-based lab experiences, whether it involves virtual or physical experimentation (Akpan and Strayer 2010; Dori and Barak 2001; Finkelstein et al. 2005a; Flick 1993; NRC 2006; NSTA 2007).

It has also been reported that students' ability to form conceptual change in inquiry-based lab settings is influenced by whether learners get to explore and manipulate variables to further understand the dimensions, tolerances and applications of the naturally occurring phenomena they are investigating (de Jong and van Joolingen 1998; Hsu 2008; Huppert et al. 2002; Stone 2007). The *open-endedness* scale used in this study measured students' ability to explore and manipulate variables in the physical and virtual lab experiences. Approximately (46%) of students viewed physical labs as being open-ended, while (74%) of students viewed virtual experiences open-ended. This difference may be described further by looking at specific question items within the open-endedness scale. For instance (75%) of students agreed with the statement "computer experiments allowed me to focus on the principles to be learned rather than the details of operating". Similarly, (70%) of students agreed with the statement that "it is easier to experiment and explore in simulated labs than regular labs", and (78%) agreed with the statement "in simulated labs, we have more time for problem solving and data analysis and interpretation". These findings are consistent with findings from other studies which have shown that virtual experiences may help students in interpreting results & manipulating variables in self-paced settings (Bell and Trundle 2008; de Jong and van Joolingen 1998; Hsu 2008; Huppert et al. 2002; Stone 2007). As was found here, virtual experiences allowed students more opportunity to explore and manipulate experimental variables than physical experiences allowed.

It has been well documented that students' ability to operate and manipulate equipment in experimental settings can impact their ability to form conceptual change (Pyatt and Sims 2007). This study measured students' ability to operate and manipulate equipment in physical and virtual lab experiences using the *equipment usability* scale. This study revealed that (50%) of students found the physical lab equipment easy to use, while (70%) of students found the virtual equipment easy to use. This difference may be described further by looking at specific question items within the equipment usability scale. For example, (53%) of students agreed with the statement "the regular labs were easier to learn and operate than the computer equipment", and (56%) agreed with the statement "the regular lab experiments worked better than the computer experiments". Furthermore, (80%) of students agreed with the statement "it was easy to learn and operate the computer simulation", and (73%) agreed with the statement "I would rather work on a computer simulation because it is easier to use than regular equipment". When asked if "computer simulations worked better than regular experiments", (69%) of students agreed. These findings suggest that, in terms of equipment operation and use, students were more successful with virtual experiences compared to physical experiences.

Therefore, with respect to the instructional value of physical and virtual experimentation, in terms of student attitudes, this study found physical and virtual experiences equivalent in the scale of usefulness of lab. On this dimension, students showed a positive attitude towards physical and virtual lab experiences. However, with respect to the scales of open-endedness and equipment usability, this study found that students had a marked preference for virtual lab experiences compared to physical ones.

How Can Inquiry-Based Lab Instruction be Designed to Promote Access

The last research question of this study dealt with access to inquiry-based lab experiences. And, even though there was no specific scale created to measure access to lab environments, there were two survey items that did attempt to measure student perceptions regarding access to inquiry-based lab experiences. When asked "I would be comfortable performing labs at home, online", (70%) of students agreed. Similarly, when asked "I prefer working online to do experiments rather than in the regular setting", (66%) of students agreed. These findings indicate that students were comfortable with virtual experimentation. This further supports arguments which have been made that hands-on can also be *virtual*. For instance, hands-on experiences may be more about data manipulation and experimentation than strict physicality of materials and equipment (Zacharia 2007; Marshall and Young 2006). Sixty-five percent of students agreed with the statement that "I would rather work on a computer simulation because it is less hazardous than regular equipment". This finding supports claims that virtual lab experiences may be effective alternatives when the experimental apparatus is too complex, dangerous, expensive, or inaccessible; or when the experimental procedure is too time consuming (Moore and Thomas 1983; Stone 2007). These findings do, however, contradict claims that virtual experimentation is an enhancement to, but not replacement for hands-on (physical) experimentation (NSTA 2007). These findings are also significant when considering recent court rulings which have set a precedent for alternatives to physical "hands-on" experimentation (Demonstration of Restructuring in Public Education 2000; Dissection Alternatives Act 2000). As has been reported, approaches to experimentation that center on physical equipment, physical material and physical facilities (Stone 2007; Lagowski 2002; Klahr et al. 2007), may be cost prohibitive (Huppert et al. 2002), and may consequently limit access (Stone 2007). When teachers and students have no access to physical equipment, virtual experimentation may be an effective alternative. Therefore, regarding access to inquiry-based lab experiences, virtual and online alternatives were viewed favorably by students.

Summary

This study investigated the instructional value of physical and virtual experimentation in inquiry-based settings. This study also investigated how inquiry-based lab experiences should be designed to promote access. This study found the instructional value of physical and virtual lab experiences were comparable in terms of student performance. Students performed equally well, and in some cases better in virtual lab experiences than in physical lab experiences. This may be due to the finding that the accuracy of a student's conceptual model is related to the quality of data obtained from the lab experience, virtual or physical. This study also found that students showed preference towards the inclusion of the virtual medium (e.g., simulations) into their lab experiences. They perceived virtual experiences as realistic, authentic, challenging, and rigorous. This study also found that the instructional value of physical and virtual experimentation in terms of student attitudes were equivalent on the scale of lab usefulness. Students showed a positive attitude towards physical and virtual lab experiences, and preferred inquiry-based experiences, physical or virtual. However, with respect to the scales of open-endedness and equipment usability, this study found that virtual experiences allowed students more opportunity to explore and manipulate experimental variables than physical experiences allowed. Students found that virtual experiences were easier to focus on principles to be learned rather than the details of operating. Students also found virtual experiences allowed more time for problem solving, data analysis, and interpretation. This study also found that, in terms of equipment operation and use, students were more successful with virtual experiences compared to physical ones. Students felt computer simulations were easier to use and worked better than regular experiments. This study also found that in regards to student access to inquiry-based lab experiences, virtual and online alternatives were viewed favorably by students.

Conclusion

This study found that students had a general preference towards the use of computers in their learning. Students felt computers were necessary tools in their learning, and tools which help them investigate complex, realistic, and challenging problems. Students expected computers to be integrated into their lab experiences. Students generally found lab experiences valuable, and viewed lab experiences as beneficial to their learning. They found value in both physical and virtual lab experiences. Students preferred lab investigations which centered on complex problems. They generally tolerated messiness in data gathering and equipment operation so long as the problem under investigation was relevant and complex, and so long as more time was spent on data analysis and interpretation than equipment operation. This was an interesting finding, given that much of the scientific research students will conduct, during and beyond beyond their high school experiences, will require familiarity and expertise in appropriate use of physical equipment and operations (Baltzis and Koukias 2009).

Students showed greater preference towards opportunities where data could be generated quickly so that it could then be manipulated and analyzed, than they did towards how the data were generated. Students found value in experimentation, and expected opportunities to explore their own experimental interest. From the students' perspective, what mattered were opportunities for exploration and manipulation of experimental variables, than equipment operation. For students, "hands-on" was more about interaction, interpretation and revelation, than it was about equipment use, physical or virtual. As was found here, hands-on can also be virtual. This suggests that virtual labs can be effective alternatives, and may be more than just substandard replacements (NSTA 2007) or inadequate substitutes (College Board 2010). This is consistent with emerging precedence which has encouraged alternative "hands-on" approaches, when necessary, to promote access and inclusion into lab science environments (Dissection Alternatives Act 2000; Demonstration of Restructuring in Public Education 2000). For instance, in cases such as rural and high-poverty schools that may not have personnel and funding to run physical labs (Watson 2007), virtual lab experiences may be plausible alternatives. If anything, these findings reveal that virtual labs are equivalent to physical labs in terms of student performance and attitudes. Contemporary approaches to hands-on learning should therefore consider that what matters most to students may not be the physicality of the equipment (Zacharia 2007), but rather the opportunity to explore and manipulate experimental variables.

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