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Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research

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A R T I C L E I N F O

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A B S T R A C T

This review presents the first attempt to synthesize recent (post-2005) empirical studies that focus on directly comparing learning outcome achievement using traditional lab (TL; hands-on) and non-traditional lab (NTL; virtual and remote) participants as experimental groups. Findings suggest that most studies reviewed (n = 50, 89%) demonstrate student learning outcome achievement is equal or higher in NTL versus TL across all learning outcome categories (knowledge and understanding, inquiry skills, practical skills, perception, analytical skills, and social and scientific communication), though the majority of studies (n = 53, 95%) focused on outcomes related to content knowledge, with most studies (n = 40, 71%) employing quizzes and tests as the assessment instrument. Scientific inquiry skills was the least assessed learning objective (n = 4, 7%), and lab reports/written assignments (n = 5, 9%) and practical exams (n = 5, 9%) were the least common assessment instrument. The results of this review raise several important concerns and questions to be addressed by future research.

1. Introduction

The U.S. National Center for Education Statistics reported that during the 2006–2007 academic year, 32% of all colleges and universities reported offering fully online degree or certificate programs (Parsad & Lewis, 2008). By 2011, nearly 3 million students were enrolled in fully online programs (Eduventures, 2012). The percentage of academic leaders who claim that online learning is critical to institutional long-term strategy has increased from 48.8% in 2002 to 70.8% in 2014 (Allen & Seaman, 2015). Furthermore, Shachar and Neumann (2010) discovered in a meta-analysis of over 125 studies comparing online distance education to face to face courses in a variety of subject areas that in over 70% of the studies, the outcome achievement for online students was better than that of their face to face counterparts. This was confirmed by a United States Department of Education meta-analysis that found, on average, students in online learning conditions performed better than those receiving face-to-face instruction (USDOE, 2010). The percent of academic leaders rating learning outcome achievement in online education as equal to or better than face-to-face instruction grew from 57.2% in 2003 to 77.0% in 2012, but then decreased in 2013 to 74.1%, and remained such in 2014 (Allen & Seaman, 2015). So, the case for online education is strengthening, and it is expected to do so for several more years (Allen & Seaman, 2010), as web-based computer-assisted learning undoubtedly brings a more fiscally efficient, opportunistic, and asynchronous education to a demographically and

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geographically wider student population (Cooper, 2005; Gröber, Vetter, Eckert, & Jodl., 2007; Scanlon, Morris, Di Paolo, & Cooper, 2002; Sicker, Lookabaugh, Santos, & Barnes, 2005).[1] In the case of science courses, however, it does so at the expense of physical presence in the science laboratory.

This discussion is very important, since research has shown that hands-on experiences in the science laboratory play a central role (arguably *the* central role) in scientific education (Hofstein & Lunetta, 2004; Hofstein & Mamlok-Naaman, 2007; Lunetta, Hofstein, & Clough, 2007; Ma & Nickerson, 2006; Satterthwait, 2010; Singer, Hilton, & Schweingruber, 2006; Tobin, 1990). This is largely due to both their presumed strong impact on student learning outcomes and performance and on their presumed practicality of professional preparation (Basey, Sackett, & Robinsons, 2008; Clough, 2002; Finn, Maxwell, & Calver, 2002; Magin, Churches, & Reizes, 1986; Nersessian, 1991; Ottander & Grelsson, 2006). However, until recent years, physical, hands-on laboratory experiences were the only experiences available from which these conclusions could be drawn.

Much research has been conducted regarding the advantages and disadvantages of the internet and computer technology on laboratory teaching and learning (e.g. Cañizares & Faur, 1997).[2] Computer-based and remote data acquisition, virtual simulations, and automated processes have all challenged and altered the methods and practices of what have traditionally been considered "hands-on" labs (Aburdene, Mastascusa, & Massengale, 1991; Albu, Holbert, Heydt, Grigorescu, & Trusca, 2004; Arpaia, Baccigalupi, Cennamo, & Daponte, 1998; Canfora, Daponte, & Rapuano, 2004; Carr, 2000; Finn et al., 2002; Forinash & Wisman, 2001; McAteer et al., 1996; Scanlon et al., 2002). All of these lab instructional modes have been discussed, from differing yet well-developed perspectives, in terms of their feasibility as stand-alone alternatives for hands-on labs (Nedic, Machotka, & Nafalski, 2003; Sehati, 2000; Selvaduray, 1995; Subramanian & Marsic, 2001; Wicker & Loya, 2000). However, no consensus has emerged regarding the impact these technological advancements might have on student laboratory learning. Some studies present data that virtual and remote labs are educational hindrances (Dewhurst, Macleod, & Norris, 2000; Dibiase, 2000; Muster & Mistree, 1989; Sicker et al., 2005; Williams & Gani, 1992), while others see them as useful supplements to the hands-on learning process (Barnard, 1985; Ertugrul, 1998; Finn et al., 2002; Hartson, Castillo, Kelso, & Neale, 1996; Hazel & Baillie, 1998; Livshitz & Sandler, 1998; Magin & Kanapathipillai, 2000; Raineri, 2001; Striegel, 2001; Tawney, 1976; de Vahl Davis & Holmes, 1971).

In support of traditional (hands-on) labs (TL), some researchers argue that there is much more information, such as many more cues, when working with real equipment. Their argument is supported by theories of presence and media richness (Daft & Lengel, 1986; Schubert, Friedmann, & Regenbrecht, 2001; Schuemie, van der Straaten, Krijn, & van der Mast, 2001; Sheridan, 1992; Short, Williams, & Christie, 1976; Slater & Usoh, 1993). Also, they argue the importance for students to be able to reconcile and explain differences between theory and experimentally derived results (e.g. experimental error), what Magin and Kanapathipillai (2000) describe as "unexpected clashes" (p. 352). Others, however, present evidence that supports non-traditional (virtual, remote) labs (NTL) as potentially sufficient replacements for TL (Cameron, 2003; Corter, Esche, Chassapis, Ma, & Nickerson, 2011; Lang, 2012; Myneni, Narayanan, Rebello, Rouinfar, & Pumtambekar, 2013; Pyatt & Sims, 2007; Zacharia & Olympiou, 2011). With NTL, students have multiple opportunities to access resources and a greater amount of time to complete specific laboratory activities, thus allowing repetition and modification, thereby fostering deeper learning (Charuk, 2010). Some research suggests, however, that students themselves are not consistent in their preferences, perceptions, and achievement of educational outcomes regarding these lab types (Cameron, 2003; Parush, Hamm, & Shtub, 2002; Vaidyanathan & Rochford, 1998).

In addition to pedagogical considerations, the economic differences between these lab types must be considered. With current fiscal cutbacks in both secondary and higher education, it is becoming increasingly difficult and costly to maintain and support laboratory equipment (Magin & Kanapathipillai, 2000). Virtual or simulated labs offer an opportunity to deliver a laboratory experience while simultaneously lessening the financial burden on the school and the student (Mahendran & Young, 1998; NCES, 2003). For example, in the case of remote labs, resources can not only be accessed at any time, but also shared and pooled across the web or between institutions (Alamo et al., 2002; Gillet, Crisalle, & Latchman, 2000; Harris & Dipaolo, 1996; Henry, 2000).[3] Conversely, it can be argued that more technology does not equal improvement, and the ultimate result could be inadequate educational laboratory experiences that are crucial to the developing professional scientist (Evans & Leinhardt, 2008).

Ma and Nickerson (2006) compiled a review of the literature concerning the comparative efficacy and perceptions of hands-on, simulated, and remote labs. They reviewed twenty articles each for remote, simulated, and hands-on labs in an attempt to identify the current state of research regarding this debate, and identify possible sources of disagreement. To ensure consistency in comparisons, the categories in this study will be based on the Ma and Nickerson (2006) definitions of these lab types. They defined virtual labs as "imitations of real experiments. All the infrastructure required for laboratories is

[1] See Wladis, Conway, and Hachey (2015) for a demographic analysis of the online STEM classroom.

[2] So much so, that Zappatore, Longo, and Bochicchio (2015) attempted to collect the most influential works in one paper in order to profile the publications and researchers and create a "pipeline" of "cleaned and normalized bibliographic references" (p. 24). The result is a useful bibliography in the field of remote lab research.

[3] Books were not reviewed in this manuscript, but for ideas and discussions on lab design, curriculum, pedagogy, system architecture, trends, research design, policies, and project collaborations relating to remote labs, Azad, Auer, and Harward (2012), Gomes and García-Zubía (2007), García-Zubía and Alves (2012), and Fjeldly and Shur (2003) are all excellent resources. For a discussion on remote lab applications for secondary schools, including teacher professional development, ICT tools, and curricular case studies, see Dziabenko & García-Zubía (2013). For remote lab design for secondary schools, see Jona et al. (2015).

not real, but simulated on computers" (p.6). They then define remote labs as being "characterized by mediated reality. Similar to hands-on labs, they require space and devices" (p.6). The difference from hands-on labs is "the distance between the experiment and the experimenter. In real labs, the equipment might be mediated through computer control, but co-located. By contrast, in remote labs experimenters obtain data by controlling geographically detached equipment. In other words, reality is mediated by distance" (p. 6). They defined hands-on labs as ones that "involve a physically real investigation process. Two characteristics distinguish hands-on from the other two labs: (1) All the equipment required to perform the laboratory is physically set up; and (2) the students who perform the laboratory are physically present in the lab" (p. 5). Because of this definition, and in an effort to minimize confounding factors in the discussion, studies involving blended learning and/or at home laboratory kits used in many distance education science classes (e.g. Reuter, 2009) were not evaluated for this review. However, the importance of such studies to the research in this field is discussed in Section 4.2 below.

Ma and Nickerson's (2006) findings suggested that no consensus existed among educators regarding the effectiveness of each lab type relative to one another, and that the educational outcomes and instruments/methods by which the effectiveness was determined seemed to vary from study to study. The purpose of this paper is to expand upon and update their findings to include literature published in and after 2005.[4] More specifically, the focus herein is on comparative studies that offer direct, empirical measures of student achievement of learning outcomes of the newer NTL (experimental group) vs. TL (control group); very few such studies had been completed at the time of Ma and Nickerson's (2006) review. The research questions for this review are the following:

(1) According to current (post-2005) empirical research, do students achieve learning outcomes as or more frequently with NTL experiences as/than with TL experiences?
(2) What learning outcomes are most frequently assessed in these comparative studies, and are outcomes consistent across all studies?
(3) What assessment tools are most frequently used to evaluate student learning outcome achievement, and are these assessments applied consistently across studies?

2. Materials and methods

As Ma and Nickerson (2006) noted in their review, the literature on this topic spans many scientific disciplines and journals. Moreover, as noted in Gröber et al. (2007), "… literature research on this topic is very time consuming and laborious since many publications are 'hidden' in conference proceedings which are not available in many cases." It was thus very difficult to find, sort, and analyze the information, and many relevant studies were likely not discovered.

An open federated search of several databases was performed in an attempt to gather relevant articles across multiple disciplines. The federated search included Elsevier/ScienceDirect, EBSCO Suite (Academic Search Premier, Applied Science and Technology Source, Education Research, Science Reference Center), JSTOR, EdITLib, and ERIC. The search was first confined to title, subject/keyword terms, and abstract, and results restricted to a date range of 2005-present. Search results were also set to include conference proceedings, government documents, journal articles, manuscripts, and dissertations, and to include results from outside the library's collection. Independent searches were performed using the basic Boolean parameters "online AND lab," "online AND laboratory," "virtual AND lab," "virtual AND laboratory," "hands-on AND lab," "hands-on AND laboratory," "simulated AND lab," "simulated AND laboratory," "simulation AND lab," "simulation AND laboratory," "physical AND lab," "physical AND laboratory," "remote AND lab," and "remote AND laboratory." Each search was also limited using the full text search parameters "learning outcome OR learning outcomes" and "learning objective OR learning objectives." To account for overlapping results within the parameter search total, a final search was performed combining all search parameters using the Boolean parameter "(online OR virtual OR hands-on OR simulated OR simulation OR physical OR remote) AND (lab OR laboratory) AND learning AND (objective OR objectives OR outcome OR outcomes)."[5] This ultimately resulted in 1291 articles for further relevance analysis.

Resulting titles were then manually filtered for relevance, first by title and then by abstract, to those specifically involving study on a science laboratory exercise used for teaching and learning, and then finally filtered to those studies that directly compared student learning outcome performance, achievement, and/or experience in NTL (experimental group) vs. TL (control group) environments. For example, studies that did not compare learning outcome achievement in *both* NTL and TL groups within the same study were not included (e.g. García-Zubía, Hernandez, Angulo, Orduña, & Irurzun, 2009; Heintz, Law, Manoli, Zacharia, & van Riesen, 2015; Marques et al., 2014). Instructional articles related to the development of remote, online, or virtual labs that focused on design, hardware, architecture, software, implementation/delivery, media, quality assurance, feasibility, etc., rather than empirical measurement of their effectiveness, were removed (e.g. Keller & Keller, 2005; Schauer, Ozvoldova, & Lustig, 2008; Gustavsson et al., 2009; Abdulwahed & Nagy, 2013; Jona, Walter, & Pradhan, 2015; Kalyan

[4] The 2005 date was chosen in an attempt to include studies that were possibly not accessible at the time of the publication of Ma and Nickerson's (2006) review.

[5] As mentioned above, the "learning AND (objective OR objectives OR outcome OR outcomes) search was a full-text search, while all other search parameters were within the title, subject/keyword, and abstract areas.

Ram et al., 2015; Kyomugisha, Bomugisha, & Mwikirize, 2015; Reischl & Mijović, 2015; Stefanovic, Tadic, Nestic, & Djordjevic, 2015; Tawfik et al., 2015; Wuttke, Hamann, & Henke, 2015). Also, articles discussing the design or effectiveness of stand-alone physical lab kits used in online science courses without the use of virtual or remote lab components were not included (e.g. Mickle & Aune, 2008; Reuter, 2009; Charuk & Mawn, 2012), nor were "blended lab" studies that evaluated the impact of virtual labs as a supplement to hands-on labs (e.g. Swan & O'Donnell, 2009).

Studies related to best practices, pedagogy, curriculum, fidelity, etc. were also excluded (e.g. Cooper, Vik, & Waltemath, 2015; Zacharia et al., 2015). Additionally, studies in which the same student participated in both the TL group and the NTL group (i.e. students first performed either the TL or the NTL, then performed the other) were not included in order to avoid the possible impact of sequence on the measured efficacy (e.g. Crandall et al., 2015; Polly, Marcus, Maguire, Belinson, & Velan, 2015). For the sake of clarity and in an attempt to limit confounding factors, studies involving haptic devices or cues were also not considered (e.g. Stull, Barrett, & Hegarty, 2013). In other words, only studies that directly compared outcomes of both TL and NTL relative to one another were considered.

Since most articles seemed to focus on technological, design, pedagogical, and/or theoretical aspects of NTL or TL, or else measured impact of only one lab mode without empirical comparison to the other or NTL labs as supplements or pre-lab exercises to TL, this filtering resulted in a surprisingly small total of 86 articles for consideration. The references cited in each of these articles were then manually scanned as before, first by title and then by abstract, for any studies involving study on a science laboratory exercise used for teaching and learning. This was especially useful for finding relevant conference proceedings and dissertations. These articles were then filtered to those studies that directly compared student learning outcome performance, achievement, and/or experience in NTL (experimental) vs. TL (control group) environments via the same criteria as above. This resulted in an additional 47 articles. These 133 (86 + 47) studies were then filtered to those articles that had clearly code-able learning outcomes and assessment instruments. Sometimes, for example, the learning outcome and/or the assessment instrument for the lab was not specified, either explicitly or implicitly (without making liberal assumptions or interpretation), so any studies that could not be confidently placed within a defined learning outcome category (see Section 3.2) and linked to a clearly presented assessment tool (see Section 3.3) was not included. This resulted in a final total of 56 articles for full-text review and coding (see Table A.1 in Appendix A). General observations, descriptive statistics, and trends were then noted and graphed.

3. Results and discussion

Overall, findings suggest that student learning outcome achievement is equal or higher in NTL versus TL across all learning outcome areas, though the majority of studies focused on outcomes related to content knowledge, with quizzes and tests being the most common assessment instrument. Outcomes and assessment tools were not consistent across studies.

3.1. Most studies show equal or greater learning outcome achievement in NTL

Studies were coded according to whether laboratory learning outcome achievement was greater in NTL, greater in TL, or equal in both. In three studies, supporting data was contingent on outcomes being measured, so these studies offered evidence in more than one of these categories (Colorado DOE, 2012; Gorghiu, Gorghiu, Alexandrescu, & Borcea, 2009; Zacharia, Loizou, & Papaevripidou, 2012), thus the graphical total exceeds 100%. The coded results can be found in Table A.1 and summarized in Fig. 1.

In a recent meta-analysis study of trends in distance and traditional learning, it was found that less than 70% of the studies published before 2002 reported results favoring online education, while in studies published after 2003, 84% of the studies favored online education (Shachar & Neumann, 2010). When focusing on empirical studies since 2005, there seems to be a similar trend when it comes to favorability and support of NTL. Clearly, the majority of studies reviewed (n = 50, 89%) claimed that student learning outcome achievement in NTL was equal to or greater than achievement in TL. An additional three

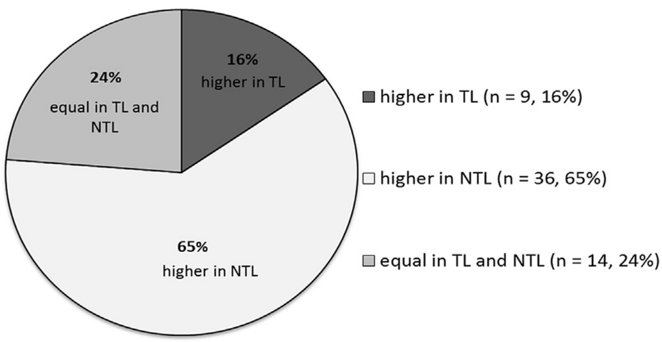

Fig. 1. Frequency of studies supporting higher (or equal) outcome achievement in NTL vs. TL.

studies that measured according to multiple outcomes contributed data in support of the same, though they also provided data that was supportive of greater outcome achievement in TL depending on the outcome being assessed.

For example, in a study where Romanian teachers designed and assessed virtual labs for their middle school science classes, it was found that the use of NTL resulted in a higher level of conceptual understanding, motivation, and hypothesis/model confirmation, but teachers expressed concern with students not learning physical skills related to handling of chemicals and chemical equipment and careful observation of real phenomena (Gorghiu et al., 2009). Zacharia et al. (2012) showed that no significant differences were found between kindergarten student learning in TL versus NTL related to a beam balance, thus suggesting that the presence of physicality is not always a requirement for understanding related concepts, but they also found that physicality was required for students who had incorrect prior knowledge of what a beam balance does. The importance of prior knowledge is corroborated in a similar study by Olympiou, Zacharias, and de Jong (2013) that is not included in this review (it was not a TL vs. NTL comparative study). They showed that simulated representations of abstract concepts increased conceptual learning of less complex underlying mechanisms, but only in students with low prior knowledge. Students with higher prior knowledge, on the other hand, benefitted from simulations of more complex underlying mechanisms. This suggests that students with high prior knowledge are able to self-construct abstract concepts of lower level complexity, but "for higher levels of complexity they need an explicit representation of the abstract objects in the learning environment" (Olympiou et al., 2013, p. 575). It also suggest that educators should be mindful of unnecessary use of NTL so as not to prevent students from being able to self-construct abstract concepts. In other words, there is clearly a need for learning with physical objects at some point, and the key is determining where along the educational process that need lies.

In a study conducted by the Colorado Department of Higher Education (2012), outcome achievement in both lab types is a result of analyzing the data from different science disciplines. Students who completed online courses with NTL had slightly lower course grades on average than students who completed courses with TL, and when disaggregated by subject, students completing biology and chemistry classes in the traditional format had statistically significant higher grades in these classes compared to students in online classes who completed NTL. This would thus support greater learning outcome achievement in TL. However, there was no statistically significant difference in the grades of physics students using either lab type.

Such a disproportion in the literature was not noted by Ma and Nickerson (2006), but their scope was not limited to empirical studies, of which there was a large increase in recent years, and of which there were few ($n = 3$, 5%) in their review. Furthermore, they reviewed no empirical studies for remote or simulated labs (see Tables V, VII, and IX in Ma & Nickerson, 2006). Thus, their conclusions were limited to observation that disagreements merely exist based on different criteria, without a discussion of the empirical basis on which the disagreements are founded. The reason for the increase in empirical studies in unclear, but it could be attributed to several possible reasons, such as novelty of the field, the questioning of position statements of certification/accreditation agencies and organizations (e.g. College Board, 2006a; College Board, 2006b; NRC, 2006; ACS, 2013; NSTA, 2013), or to circumstances of increased funding and support (NSF, 2008).[6]

3.2. Learning outcomes varied, but content knowledge was most frequently assessed

It has been previously noted that significant disagreement exists among science educators regarding the means and purpose of the laboratory component in science courses (Kang & Wallace, 2005). This disagreement has spilled over into online science learning, and it appears that it may be the single biggest factor in the debate regarding the efficacy of NTL versus TL, which confirms previous findings (Elawaday & Tolba, 2009; Ma & Nickerson, 2006). The learning outcomes for labs in the studies reviewed varied considerably, and as such, a claim of student achievement of learning outcomes in either lab modality could simply be contingent upon the outcome being measured (and how it is measured—see Section 3.3). To address this concern, and in an effort to consolidate the results and thereby simplify comparisons and coding, a 6-category tool (KIPPAS) was developed for this review after analyzing the literature search results. The tool was designed around the National Research Council (NRC) goals of laboratory experiences and incorporated the eight essential practices of science and engineering as outlined by the NRC (NRC, 2006, pp. 3–4; NRC, 2012), but was also influenced by the position statement of the National Science Teachers Association regarding the integral role of laboratory investigations in science instruction (NSTA, 2013). The learning outcome categories are explained in Table 1.

Ma and Nickerson (2006) also developed a tool for their review, which was largely centered on the goals proposed by the Accreditation Board for Engineering and Technology (ABET, 2005). However, due to the applied sciences (i.e. engineering) no longer dominating the literature on this topic, a more inclusive tool was needed to effectively incorporate the natural sciences (ergo the categories of Inquiry Skills and Analytical Skills) as well as new trends in the research (the Perception category). The KIPPAS tool was then used to categorize the 56 studies of this review in order to be able to make fruitful comparisons, and the results can be found in Table A.1 and summarized in Fig. 2.

Occasionally, learning outcomes were stated directly in the study (i.e. Finkelstein et al., 2005), but most often they were implicit within the lab description or the discussion and conclusion sections of the study. In some cases where objectives

[6] Of the studies reviewed, 11% ($n = 6$) explicitly acknowledged the NSF as a funding source (Finkelstein et al., 2005, 2006; Flowers, 2011; Klahr et al., 2007; Srinivasan et al., 2006; Winn et al., 2006).

Table 1
The **KIPPAS** categories of intended outcomes for laboratory learning.

Learning outcome	Description	NRC 2006 Lab goals	NRC 2012 practices
Knowledge & Understanding	The degree to which students model theoretical concepts and confirm, apply, visualize, and/or solve problems related to important lecture content	Enhancing mastery of subject matter	1, 2, 5, 6, 7
Inquiry Skills	The degree to which students make observations, create and test hypotheses, generate experimental designs, and/or acquire an epistemology of science	Developing scientific reasoning; Understanding the nature of science	1, 2, 3, 5
Practical Skills	The degree to which students can properly use scientific equipment, technology, and instrumentation, follow technical and professional protocols, and/or demonstrate proficiency in physical laboratory techniques, procedures, and measurements	Developing practical skills	2, 3
Perception	The degree to which students engage in and express interest, appreciation, and/or desire for science and science learning	Cultivating interest in science and interest in learning science	–
Analytical Skills	The degree to which students critique, predict, infer, interpret, integrate, and recognize patterns in experimental data, and use this to generate models of understanding	Developing scientific reasoning; Understanding the complexity and ambiguity of empirical work	2, 4, 5, 6, 7, 8
Social & Scientific Communication	The degree to which students are able to collaborate, summarize and present experimental findings, prepare scientific reports, and graph and display data	Developing teamwork abilities	8

Note. The eight practices of science and engineering that the NRC *Framework* identifies as essential for all students to learn and describe in detail are listed below.
1. Asking questions (for science) and defining problems (for engineering).
2. Developing and using models.
3. Planning and carrying out investigations.
4. Analyzing and interpreting data.
5. Using mathematics and computational thinking.
6. Constructing explanations (for science) and designing solutions (for engineering).
7. Engaging in argument from evidence.
8. Obtaining, evaluating, and communicating information.

were specifically stated, they tended to be overly technical and specific to the lab tasks at hand (i.e. Sicker et al., 2005), and the higher level KIPPAS classification was inductively gleaned from the details provided.

3.2.1. Knowledge & understanding (K)

Nearly all of the studies reviewed (n = 53, 95%) addressed *K*, and 87% (n = 46) of those studies provided evidence for equal or greater student learning outcome achievement in NTL compared to TL. Interestingly, in 38% (n = 20) of studies addressing

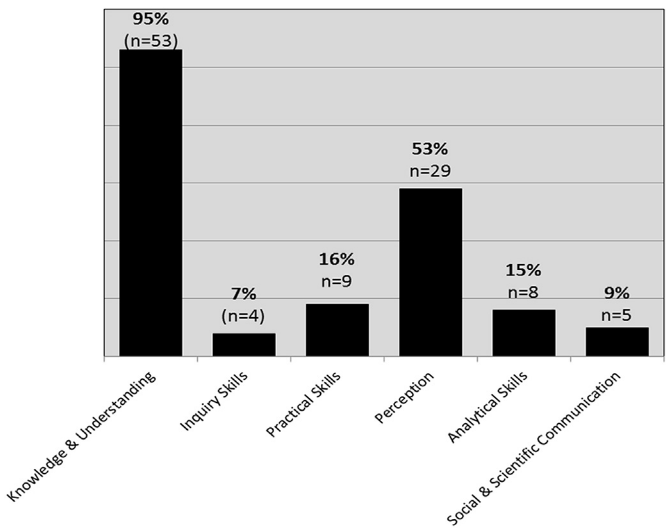

Fig. 2. Frequency of studies assessing each KIPPAS outcome. Totals do not equal 100% since some studies addressed multiple outcomes.

K, it was the only outcome measured, and all of these studies provided evidence of higher or equal learning outcome achievement in NTL compared to TL. Ma and Nickerson (2006) also found that almost all studies they reviewed addressed conceptual understanding (n = 59, 98%), but only 15% (n = 9) of those used it as the only measured learning objective. Similar to this review, they also found that most (n = 7, 78%) of the studies using conceptual understanding as the sole measurable objective concerned NTL (n = 5 for remote labs, n = 2 for simulated labs). Thus, it appears that many of the studies contributing to the increase in literature in this field since 2005 primarily assess the *K* outcome. This raises an important question regarding the purpose of the educational science laboratory and what outcomes should determine pedagogical efficacy. It is worth noting, however, as shown in Table 1, five of the eight practices of science and engineering that the NRC *Framework* identifies as essential for all students to learn and describe in detail are, in fact, associated with knowledge and understanding (NRC, 2012).

3.2.2. Inquiry skills (I)

Despite inquiry being at the core of scientific learning, the bulk of science laboratory courses, whether traditional or non-traditional, have been shown to be consistently expository in nature (Lagowski, 2002). This means that the most widely adopted approach to teaching science labs “is teacher-centered in that the laboratory activities are carried out in scripted, pre-determined fashion under the direct supervision of the instructor,” with the purpose being to “clarify and/or validate existing scientific principles and theories” (Pyatt & Sims, 2007, p. 870). However, according to Pyatt and Sims (2007):

> “Such approaches are problematic because they do not provide opportunities for students to truly explore the limitations of the equipment, materials, and theory they are trying to validate. Nor do they provide opportunities for students to create their own understanding of the phenomena they are investigating. Rather, the expository environment utilizes rote procedures which inhibit students from forming a genuine understanding of the connections between the data they collect and the theories the data describe (Eylon & Linn, 1988)” (p. 870).

Such a laboratory approach directly contradicts the process of scientific inquiry, so both TL and NTL at most colleges and universities, for example, may not be meeting the standards set forth for science laboratory education (cf. NRC, 1996; NRC, 2000; NRC, 2006; NRC, 2012; NSTA, 2013).

This pattern is also reflected in the current findings. Only 7% (n = 4) of studies measured *I* as an outcome, and it was never the sole outcome being measured. All of these studies provided evidence supporting equal or higher learning outcome achievement in NTL—there were no studies assessing the *I* outcome that supported higher learning outcome achievement in TL. Klahr, Triona, and Williams (2007) assessed this outcome by having students design, build, test, and analyze mousetrap cars (both in the physical control group and virtual experimental group), which required them to draw on previous experience and observations to form and test hypotheses about which components would result in the best performance. Both Morgil, Gungor-Seyhan, Ural-Alsan, and Temel (2008) and Tatli and Ayas (2012) provided students with various virtual chemistry labs in which they could manipulate values and variables, and then had them generate a research question and design that could utilize the virtual labs to answer the question. Lang (2012) surveyed students on their perceptions regarding whether they had experiences in the lab reflecting the design skills learning objective presented by Ma and Nickerson (2006), which is a component of *I*, but no students responded positively that this learning objective was achieved.

The importance of inquiry in the science learning process is highlighted by the fact that it is addressed throughout the *National Science Education Standards* (NRC, 1996). In addition, the National Research Council produced an entire document dedicated to guidance on the topic (NRC, 2000), and as shown in Table 1, four of the eight practices of science and engineering that the NRC *Framework* identifies as essential for all students to learn and describe in detail are associated with scientific inquiry (NRC, 2012). Schwab (1962) recognized long ago the need for science learning to reflect the actual ways in which scientists go about their work. He stressed that “scientific research has its origin not in objective facts alone, but in a conception, a construction of the mind” (p. 12). From this viewpoint, it would thus be necessary to go beyond *K*, and thus beyond facts and results of investigations, in order to show how “these products were derived by scientists—how a body of knowledge grows and how new conceptions come about” (Chiappetta & Koballa, 2010, p. 125). Therefore, it is important for future studies to include in their comparisons of effectiveness more empirical data concerning this learning outcome.

3.2.3. Practical skills (P_r)

Science educators most frequently reference P_r as that which cannot be taught using NTL, and that which in itself provides substantial benefit of TL over NTL (NRC, 2006). So, one would perhaps intuitively expect a disproportion of P_r achievement in favor of TL when this outcome is measured. However, 16% (n = 9) of studies reviewed measured P_r, and 78% (n = 7) of them demonstrated equal or higher learning outcome achievement in NTL. When students completed virtual labs and were then given a face-to-face practical, they performed better than those students who completed the same lab in a traditional (face-to-face) manner. Practical tests included physical building and testing of circuits (Farrokhnia & Esmailpour, 2010; Finkelstein et al., 2005, 2006), a horticulture plotting assessment (Frederick, 2013), setup of an electrochemical cell (Hawkins & Phelps, 2013), and robotic programming (Tzafestas, Palaiologou, & Alifragis, 2006). Lang (2012) surveyed students on their perceptions regarding whether they had experiences in the lab reflecting the professional skills learning objective presented by Ma and Nickerson (2006), which is a component of P_r. Students in both the TL and NTL groups were asked to identify from a list those skills with which they became more familiar after completing the lab. The results indicated that participants in the control (TL) group chose an average of 2 skills each, while the experimental (NTL) group chose an average of 3.3 skills each.

Though these results are without proof of statistical significance and based on student perception and no actual instructor measurement of skill proficiency, they nonetheless suggest an interesting avenue of further investigation.

It is claimed that TL "have advantages when the instructional goal is to have students acquire a sophisticated epistemology of science, including the ability to make sense of imperfect measurements and to acquire practical skills" (de Jong, Linn, & Zacharia, 2013, p. 307). At a deeper pedagogical level, they can capitalize on tactile information that cognitive research shows cultivates conceptual knowledge development (Barsalou, 2008; Zacharia et al., 2012). Setting up and troubleshooting equipment, careful experimental observation, messy data, and real experimental time scale are just a few of the realities that are believed to be taught better using TL, but little empirical evidence seems to exist that support their being a better means to do it than NTL.

Others would argue that such a point is moot. Pickering (1980), for example, argued that the majority of students in science laboratory classes do not have a career goal of becoming a professional scientist. Further, many of the skills students learn in laboratories are obsolete in science careers. If these skills are worth teaching, it is as tools to be mastered for basic scientific inquiry and not as ends in themselves. So if a consensus were to form accepting TL as a better means of teaching P_r, Pickering would likely argue that it should have little impact in the overall argument.

3.2.4. Perception (P_e)

It is interesting to consider that students' perceptions of the laboratory experience may have more cognitive impact on them than the actual content or psychomotor means associated with its completion. Magin and Kanapathipillai (2000) point out that the conversation about the extent to which NTL could or should replace TL is devoid of research explaining how students themselves view the role of laboratory learning. P_e was subdivided into student perception and instructor perception in Table A.1. Of the studies reviewed, over half (n = 29, 52%) assessed P_e, and 86% (n = 25) of these studies provided evidence for equal or higher outcome achievement in NTL.[7] P_e was almost always assessed in conjunction with other learning outcomes—only 10% (n = 3) of studies that assessed P_e assessed it alone. Interestingly, of the nine studies in this review that demonstrated higher learning outcome achievement in TL, 67% (n = 6) of them did so with P_e, with 50% of them utilizing quantitative methods (n = 3) and 50% using qualitative methods (n = 3). Most data supporting higher outcome achievement in TL was largely a result of assessing P_e, and this data was mostly qualitative. These findings perhaps reinforce the idea that though one may have a preference for a TL over NTL modality, this preference might be socially rather than technologically determined (Nowak, Watt, & Walther, 2004).

In contrast, 44% (n = 22) of those studies that demonstrated equal or higher learning outcome achievement in NTL used P_e data to do so. Only 9% (n = 2) of those studies (Chan & Fok, 2009; Collier, Dunham, Braun, & O'Loughlin, 2012) assessed P_e alone. All studies assessing P_e for both TL and NTL did so subjectively via surveys, questionnaires, interviews or observations. The large majority of these studies (n = 25, 86%) focused only on student P_e, but a small number of them (n = 2, 7%), such as Collier et al. (2012) and Gorghiu et al. (2009), focused on instructor P_e. An additional 7% (n = 2) of studies (Rajendran, Veilumuthu, & Divya, 2010; Scott, 2009) assessed both student and instructor P_e.

So how much emphasis should be placed on P_e as a learning outcome, and of what value is student achievement of P_e? As shown in Table 1, none of the eight practices of science and engineering that the NRC *Framework* identifies as essential for all students to learn and describe in detail are associated with perception (NRC, 2012). This is perhaps problematic, since research has shown that the way information or an experience is represented is very important to the learning process (Rieber, 1996). Also, dispositions have a powerful influence on student engagement and science learning (Koballa & Glynn, 2007); students who leave school with favorable science-related dispositions are likely to be lifelong science learners and informed science-related decision makers (Koballa, Kemp, & Evans, 1997). If information is perceived to be represented in a manner that ultimately affects students' self-confidence, it could have a large impact on laboratory completion and performance (Corsi, 2011). One of the studies reviewed herein, for example, provided data suggesting that student attitudes were a predictor of performance (Morgil et al., 2008).

Also, low levels of satisfaction and motivation have been linked to a higher attrition rate, especially in online education (Trindade, Fiolhais, & Almeida, 2002), but research suggested over thirty years ago that simulations, for example, could considerably increase student motivation (Brawer, 1982). Though some researchers suggest that the richness of media does not matter, and that we adapt to whatever media are available (Korzenny, 1978), others claim that the key factor in this motivation is the relevancy or realism of such a non-traditional environment (Orbach, 1979). Gröber et al. (2007) claims, for example, that the lab should be as authentic and transparent as possible for the user, and that the experiment should come across as a common "real" experiment carried out in a TL environment. Students should not perceive the experiment as "fake," such as was the case in Srinivasan et al. (2006). Such authenticity is also discussed elsewhere in the research (Auer, 2001; Cartwright & Whitehead, 2004; Cooper, 2005; Ferreira & Müller, 2004; Forinash & Wisman, 2005; Kennepohl, Baran, Connors, Quigley, & Currie, 2005). Nickerson, Corter, Esche, and Chassapis (2007) note that more and more instruments are controlled by mouse and keyboard, and developments in computer technology continually replace

[7] Higher perception of outcome achievement in NTL is also supported in many other studies that did not meet inclusion criteria for this review. For example, Marques et al. (2014) and García-Zubía et al. (2009) demonstrated that students perceived equal or greater outcome achievement in NTL, but their papers were not included herein because it analyzed outcomes of students who participated in an NTL experience only, without comparison to a TL group.

components of laboratory instrumentation, making the operation of equipment remotely or in person more the same than different. Such fidelity has increased exponentially in recent years.

3.2.5. Analytical skills (A)

Very few studies (n = 8, 14%) addressed *A* as a learning outcome, even though, as shown in Table 1, six of the eight practices of science and engineering that the NRC *Framework* identifies as essential for all students to learn and describe in detail are associated with analytical skills (NRC, 2012). The fact that not many studies measured this outcome is perhaps not too surprising given that the vast majority of studies involved undergraduate students or below, and the undergraduates were often not science majors. However, these skills should not be reserved only for science majors. The National Association of Colleges and Employers listed analytical skills as one of the most important characteristics (second only to communication skills) that potential employers desire and feel is lacking in current college graduates (Koc & Koncz, 2009). So more frequent inclusion and assessment of this learning outcome, even in general education and non-majors courses, is certainly warranted.

In the studies analyzed, *A* was never the sole learning outcome being measured, and it was almost always measured with at least two other outcomes. Of the studies that assessesed *A*, 88% (n = 7) provided evidence of equal or greater learning outcome achievement in NTL. Assessments for this outcome ranged from formal lab reports (Lang, 2012) to open ended quiz questions regarding data interpretation (Bakar & Badioze Zaman, 2007; Pyatt & Sims, 2007, 2012; Yang & Heh, 2007) to interpretation of original data to answer an original research question (Morgil et al., 2008) to oral interviews conducted with learners regarding data interpretation (Tatli & Ayas, 2012). Sicker et al. (2005) was the only study who found analytical outcome achievement to be greater in TL. Their assessment was open-ended data interpretation questions in the form of a "mini" lab report.

3.2.6. Social & Scientific Communication (S)

Researchers have argued that to accurately reflect the "doing" of science in the real world, students, like scientists, should be given more opportunities and time to discuss their ideas, write about them, develop presentations, and to communicate with others (Michaels, Shouse, & Schweingruber, 2008). Scientists themselves agree on the importance of this skill in their professional lives and in real-world science—81% of scientists surveyed stated that they would be willing to invest time in learning how to explain their work more clearly to the public (Hartz & Chappell, 1997). With not only the internet, but the advent and popularization of 24 h news, social media, blogging, mobile devices, etc., formal academic filters are less frequently in place when it comes to disseminating scientific information, and these "interlaced yet disconnected parts create the perfect recipe for propagation of inaccurate information" (Dees & Berman, 2013, p. 384). Chappell and Hartz (1998) state that colleges and universities should do a better job teaching these skills in science courses, suggesting that science courses should "include information on technical writing, but also should teach communications skills helpful in addressing the public, such as how to present an article about a scientific discovery as a detective story, and how to present new knowledge in graphic terms" (p. B7).

In addition, communication with scientific peers is a necessary skill. In almost all instructional science laboratory courses, learning occurs in groups. Research has shown that cooperative learning can improve achievement and mastery of content (Slavin, 1989), as well as develop a positive classroom environment (Kagan, 1989). This can be true of online courses as well—Mawn (2007) described how online undergraduate chemistry students discussed and analyzed data through class discussions, which produced more questions and more cycles of inquiry. Similar results were found with undergraduate physics students (Mawn & Emery, 2007). It was determined that unlike face-to-face interactions in a TL classroom, where less interaction and few questions by students are often observed (Fetaji, Loskovska, Fetaji, & Ebibi, 2007; Tatli, 2009), asynchronous online interactions provided opportunities for sharing, support, and reflection among all, not just some, participants (Mawn & Emery, 2007).

For the sake of clarity in this review, however, group work alone was not sufficient for categorization into *S*; only studies that deliberately assessed it as an intended learning outcome were classified in this category. Such was the case in 9% (n = 5) of studies reviewed. Interestingly, nearly all (80%, n = 4) of the studies assessing this outcome demonstrated student achievement to be equal or higher in NTL. Only Sicker et al. (2005) provided data related to higher achievement of this outcome in TL—students summarized and presented their findings as formal lab reports, and the grades of TL students were higher than NTL students. Formal lab reports were also assessed in Lang (2012), but no significant differences in performance were found. Finkelstein et al. (2005) reported that when asked to compose a write-up explaining and presenting the results of the experiment "in everyday language so that a friend who has never taken physics would understand your reasoning" for their interpretations, NTL students outperformed TL students. Morgil et al. (2008) assessed formal in-class group presentations of results from both lab types as part of a project that ultimately provided data in support of equal or greater outcome achievement in NTL.

In one study, both NTL and TL students participated in Peer Instruction (Finkelstein et al., 2006). In this method, a demonstration is given and a question is presented. First the students answer the question individually using personal response systems before any class-wide discussion or instruction. Then, students are instructed to discuss the question with their neighbors and answer a second time. Thus the effect of collaboration can be compared in both groups, and its effect was found to be significantly higher in the NTL group, suggesting that, at least in this case, NTL work led to more fruitful discussions. Given the importance of *S* to both science learning and public scientific literacy, it is recommended that future studies address this learning outcome more deliberately and in more statistical detail.

3.3. The studies used a variety of instruments by which to assess learning outcomes

Studies were categorized according to the instrument used to assess the learning outcomes. The results are found in Table A.1 and summarized in Fig. 3. The majority of studies (n = 39, 70%) used quizzes or exams as the primary instrument of outcome assessment. This likely correlates directly with the fact that the vast majority of studies (n = 53, 95%) also addressed *K*, and formal objective assessments are the most common means of assessing this outcome. Lab reports or written assignments (n = 5, 9%) were primarily used in those studies that addressed *S* (i.e. Finkelstein et al., 2005; Finkelstein et al., 2006; Lang, 2012). Though lab reports and written assignments are perhaps most reflective of the way science is actually communicated, they are difficult to use as an assessment of effectiveness for this field of research given the inherent subjectivity in the grading process and the variable of different graders across studies. In an effort to lessen confounding effects on this discussion, perhaps development of a standardized rubric by researchers in this field of study could be agreed upon, or at minimum an agreement reached to be transparent with the rubric used in the study.

Surveys and questionnaires (n = 22, 39%) were the second most frequently used instrument used to measure effectiveness, and they were primarily used to assess P_e −91% (n = 20) of studies addressing perception did so with surveys and questionnaires. Winn et al. (2006) utilized a survey, but it was only used to gather demographic data about the students completing the lab. These may be the only way to address issues related to attitudes, perceptions, and demography, but one might question the role of a Likert Scale survey to directly assess *K* by merely asking students if the agree or disagree whether the learned the lab content, as was the case in Arjamand and Khattak (2013).

Interviews were used in 18% (n = 10) of studies, and in most cases (n = 7, 70%), they were used to assess P_e (n = 3 for student perception, n = 3 for instructor perception, and n = 1 for both student and instructor perception). In addition to using interviews to assess both student and instructor perceptions, Tatli and Ayas (2012) also used observations to determine the degree to which instructors fostered a constructivist learning environment, and later again in a different study (2013) they used both instruments to subjectively assess *K* by confirming test results. Zacharia et al. (2012) relied on interviews to assess *K* as well, but the research subjects were kindergarteners, so the interview was essentially an oral content assessment. Finkelstein et al. (2005), however, used observations to assess P_r in physics students while constructing circuits.

Given the high emphasis that advocates of TL place on physicality and psychomotor laboratory experiences (NRC, 2006), it is perhaps surprising that more studies do not quantitatively compare these methods via traditional laboratory practical exams. Only 9% (n = 5) of studies used this method to compare learning outcome achievement in NTL versus TL. Of the five, only one was able to provide evidence of greater outcome achievement in TL. Students were divided into NTL and TL groups, where the former group learned and performed microscopy in a virtual lab setting, and the latter learned and performed it in a live microscopy setting (Parker & Zimmerman, 2011). The skills were then assessed in a physical lab with physical instrumentation, including mounting, centering, focusing, and magnification of specimens. Students in the TL group performed significantly better. However, similar studies involving a horticulture plotting assessment (Frederick, 2013), setup of an electrochemical cell (Hawkins & Phelps, 2013), robotic manipulation (Tzafestas et al., 2006) and the physical building of circuits (Farrokhnia & Esmailpour, 2010) yielded the opposite result—that the NTL group significantly outperformed the TL group. Intuitively, P_r would perhaps be the most contested outcome of NTL versus TL, so further studies such as these (with variable instruments of assessment, perhaps) would go far in helping frame the NTL versus TL discussion.

Student course grade or GPA is likely the least discriminating instrument by which to measure learning outcomes, though it was used to do so in 11% (n = 6) of studies reviewed. There are many variables that could impact a student's grade or GPA,

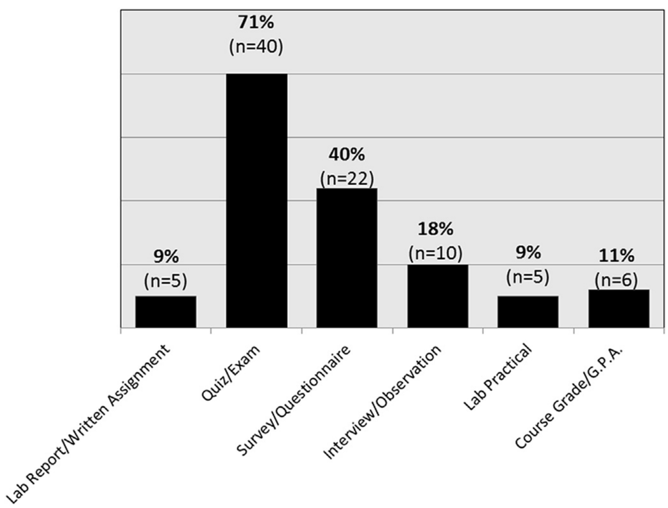

Fig. 3. Frequency of studies using each evaluation instrument to assess achievement in NTL and TL.

and it is nearly impossible to identify let alone control these variables. Only two of these studies showed higher learning outcome achievement in TL, while the other four suggested equal or better outcome achievement in NTL. Scott (2009), using extracted aggregated data, showed that students who complete science courses using NTL have significantly lower mean course grades than do students who completed courses with TL, as well as a lower passing rate overall. She admits, however, that grades may be reflective of other factors. Sicker et al. (2005) focused on the grades of a single class, and suggests that TL students out-perform NTL students on class grades. However, the claims were not verified with tests of statistical significance due to small sample size. Interestingly, Colorado DOHE (2012) compared students who completed courses with NTL with those who completed TL in biology, chemistry, and physics. They found that the TL group earned significantly higher grades in biology and chemistry, but found no statistically significant difference between grades of students in NTL and TL physics classes.

The high frequency of quizzes and exams as an assessment instrument, though not surprising, is an interesting finding. Though these forms of assessment are ubiquitous in science classrooms around the world, it seemingly perpetuates the myth that science is, in fact, a body of conceptual knowledge more than it is a systematic way of thinking and observing the natural world. Their convenience and easily quantifiable results are likely what makes their use most appealing, but given the lack of clarity that already exists in this field of research regarding learning outcomes, it is extremely important that quizzes and tests, if continued to be used, be valid and measure what they claim to measure, and be reliable in order to provide consistent information over time (Borg & Gall, 1983). Perhaps, in order to truly assess the depth of the KIPPAS outcomes, alternative assessment instruments besides the six aforementioned could be used to gain richer understandings of what students are thinking and how they construct meaning. Examples might include concept mapping, illustrations, a lab journal, KWL (know, want or will, learned) charts, model construction or a portfolio (Chiappetta & Koballa, 2010).

4. Conclusions

This paper has reviewed 56 studies related to student learning outcome achievement in NTL versus TL, and determined that the data in the current body of comparative empirical literature suggests that learning outcomes can be achieved at an equal or greater frequency with NTL, regardless of the outcome category being measured. However, the degree of difference in achievement is dependent upon the outcome category. Studies supporting higher achievement in NTL seem to place a lot of emphasis on content knowledge and understanding (and thus quizzes and exams as the instrument of assessment), whereas studies supporting higher achievement in TL seemed to rely heavily upon qualitative data related to student and/or instructor perception (and thus surveys as the instrument of assessment). The disagreement among science educators regarding the means and instructional purpose of the laboratory (i.e. learning outcome preference) appears to be a large factor in the debate regarding the efficacy of NTL versus TL.

4.1. Implications of this research

The overall lack of general consensus regarding the “effectiveness” of NTL versus TL in science education confirms recent findings (Ma & Nickerson, 2006; Elawaday & Tolba, 2009; Oloruntegbe & Alam, 2010). The question posed 35 years ago by Bates (1978), even long before the current boom in educational technology, still stands unanswered: “What does the laboratory accomplish that could not be accomplished as well by less expensive and less time consuming alternatives” (p. 75)?

Data that reflected no significant difference between outcome achievement (i.e. NTL and TL being equally “effective”) was graphed as “equal” outcome achievement in both modalities. According to Equivalency Theory as it applies to online or distance education, it is possible that such “equality” data is additive to the “higher in NTL” data, thus strengthening the case for NTL (Simonson, Schlosser, & Hanson, 1999). From this perspective, if the empirical data can support that NTL can offer at least an equivalent effect of achieving intended learning outcomes as TL, given their many other affordances, including but not limited to removal of confusing lab details and corresponding highlighting of salient information (Trundle & Bell, 2010), modification of time scale (Ford & McCormack, 2000), the ability to observe otherwise unobservable phenomena (Zacharia & Constantinou, 2008; Deslauriers & Wieman, 2011; Jaakkola, Nurmi, & Veermans, 2011; Zhang & Linn, 2011), less setup time and faster results (Zacharia, Olympiou, & Papaevripidou, 2008), minimization of distractions, authentic measurement error, or equipment aberrations (Pyatt & Sims, 2012), cost effectiveness (Toth, Morrow, & Ludvico, 2009), better accessibility for students with disabilities (Grout, 2015), and access to otherwise inaccessible experimental systems (McElhaney & Linn, 2011), without sufficient empirical refutation, an argument can be made for their acceptance as replacements to their traditional counterparts. On the other hand, these very attributes could serve as evidence in support of TL, stressing their importance to real-life science (Renken & Nunez, 2013; Toth et al., 2009). As highlighted in Section 3.2, it becomes a matter of perspective, focal difference, and instructor preference of learning outcomes.

If the data continues to accumulate and provide empirical evidence that equal or greater learning outcome achievement can occur with NTL, it may challenge current positions of some accrediting, certifying, and standards/quality assurance organizations. Such evidence could, for example, make a case (at least situationally) for NTL being

> … an acceptable, accessible, and cost-effective alternative to in-person, hands-on labs. Research to confirm equivalent outcomes would also mean that governing organizations like the College Board, ACM, and NSTA should consider

> simulated labs equivalent to hands-on labs and, thus, acceptable practices for science laboratory requirements. If this occurs, the definition of "hands-on" will no longer be limited to students touching physical materials, but will instead emphasize their mental "minds-on" engagement with the science topics they are studying.
>
> (Frederick, 2013, pp. 6–7)

Further empirical studies related to learning outcome achievement (and perhaps degree of differences in achievement) by category are needed to answer such questions of efficacy. Large variability in the outcomes being measured could actually benefit the discussion, but discussions and conclusions must be within clear categorical boundaries (i.e. use a KIPPAS-like categorization), with any instructor preference or weighted importance of one category over the other made transparent. Otherwise, meaningful, unambiguous comparisons cannot be made.

As a specific example of the impact this conversation could have on such positions towards NTL, several years ago the College Board, the agency that accredits Advanced Placement (AP) secondary level classes for college credit in the United States, issued a position statement saying that virtual labs could not be part of a school's AP curriculum (College Board, 2006a), though this statements was recanted within months (College Board, 2006b). Currently, any courses wanting to receive AP accreditation must submit a proposal and justification for the use of any virtual labs, and must receive written permission from the College Board, but curriculum standards are being rewritten for clarity in light of this issue, and it is surmised that soon no conditional authorization will be permitted. Also in the United States, the National Science Teachers Association (NSTA, 2013) and the American Chemical Society (ACS, 2013) explicitly denounce the substitution of NTL for TL. These agencies influence or establish the standards by which science teachers and chemistry programs are accredited.

As another example, in the U.K., the Quality Assurance Agency for Higher Education (QAA) uses more flexible language in its benchmark statement for biosciences, stating that, "teaching and learning strategies in the biosciences are not static but are adapted to changes in philosophy and technology; current strategies take place within a framework that may include … laboratory classes, computing/simulations, the use of bioinformatics tools and/or fieldwork," and that, "laboratory classes, fieldwork and 'in-silico' approaches to practical work (e.g. modeling, data mining) support learning in the biosciences" (QAA, 2007, p. 8). The QAA benchmark statement for chemistry also is not clear as to the extent of acceptance of NTL as suitable replacements for TL, stating simply that chemistry students should develop "chemistry-related practical skills, for example skills relating to the conduct of laboratory work" (QAA, 2014, p. 10). When these skills are delineated in Section 5.5 of the benchmark statement, most seem to be cognitive skills (i.e. "ability to determine …," "ability to find …," "ability to plan …," "ability to interpret …," etc.), and for those that are not, the language is not specific enough to exclude the possibility that they cannot be attained with NTL. Depending on interpretation, for example, one could argue that even the "skills in the operation of standard chemical instrumentation" could be achieved through remote lab experiences (QAA, 2014, pp. 10–11). Similar language and arguments can be found/made in the European Commission's Tuning Project (an approach to implement the Bologna Process in higher education) involving common reference points and benchmarking in university chemistry programs across Europe (Tuning Project, 2000–2004). No language exists therein that explicitly excludes NTL as the mode for meeting these benchmarks. Thus, as the NTL vs. TL efficacy data accumulates and becomes clearer, it could drive changes in language and clarity of these benchmarks.

Program entry requirements and transfer/articulation agreements could be affected by this NTL versus TL discussion as well. Many pre-professional schools in the United States are not accepting for transfer online courses that utilize NTL.[8] For example, according to the 2007 Articulation Agreement between Mississippi Board of Trustees of State Institutions of Higher Learning (IHL) and Mississippi State Board for Community and Junior Colleges, the articulation agreement does not allow for online science courses to be accepted for admission into the School of Pharmacy, Medical School, or Dental School (Scott, 2009). Community and Junior Colleges are a very important link to a 4-year degree and/or a pre-professional program for many students (Cohen & Brawer, 2003). Such explicit language was unable to be found in admission and program requirements of universities outside of the United States, though position clarification may be necessary if NTL become increasingly utilized.

4.2. New concerns and questions

The results of this review raise several important concerns and questions to be addressed by future research. For example, in terms of general science pedagogy, a few studies (Tatli & Ayas, 2012; Yang & Heh, 2007; Zacharia & Constantinou, 2008) offered evidence that NTL were equally or more effective as/than TL at enabling use of the constructivist approach to teaching and learning, which emphasizes the importance of learners taking an active role in their own learning (Bruner, 1961; Piaget, 1960). According to Triona and Klahr (2003) and Klahr et al. (2007), the assumption that only the physical manipulation of laboratory objects (e.g. TL) can enhance learning is not required in either constructivist or cognitive learning theory. According to Zacharia and Constantinou (2008), "cognitive theory focuses on the need for learners to actively process information and practice the target skill. Neither a theoretical nor an empirical justification exists that portrays physical

[8] Of the studies reviewed herein, 11% (n = 6) took place at medical schools (Barbeau, Johnson, Gibson, & Rogers, 2013; Braun & Kearns, 2008; Collier et al., 2012; Husmann, O'Loughlin, & Braun, 2009; Krippendorf & Lough, 2005; Scoville & Buskirk, 2007), and all of them provided data supporting equal or greater achievement of learning outcomes in NTL.

manipulation of materials as a requirement for active processing and practice, unless the target skill is perceptual-motor" (p. 428). Empirical data regarding the pedagogical argument of constructivist theory as it applies to NTL versus TL warrants further pursuit.

Also, it is important for future research to measure lab type effectiveness relative to student grade level and cognitive/psychological development. With the proliferation of educational technology, coupled with the increase in the number of online elementary and secondary schools and parents choosing to home school, the impact of this debate of student outcome achievement in each lab modality reaches far beyond college/university undergraduate education. For example, in 2000, roughly 45,000 k-12 students in the United States took an online course, and by 2009, that number rose to more than 3 million (Horn & Staker, 2011). This was accompanied by a simultaneous explosion in home schooling—from roughly 800,000 students in 1999 to roughly 2 million in 2011, and research projects that by 2019, 50% of all high school courses will be delivered online (Christensen, Horn, & Johnson, 2008). This will likely result in a much greater use of NTL, so gauging student outcome achievement at different grade level or stages of psychological development is extremely important not only for the development of sound pedagogical best practices, but also for fiscally responsible school administration.

Another possible avenue of future research lies within the technological development of the NTL sources. Virtual laboratory technology is becoming more manipulative, interactive, and "real" by the day, and the future of the technology is very promising. For example, the production and use of 3D human anatomy dissection images in an online Anatomy and Physiology lab course have already been described that utilize 3D glasses (Kolitsky, 2012), and haptic devices are offering more dimensions to the virtual laboratory experience (Stull et al., 2013).

A growing topic in this field is an approach known as the "blended" or "hybrid" approach to laboratory learning. In this type of lab, both TL and NTL modalities are combined in an attempt to capitalize on the benefits of both—namely the economic benefit and feasibility for achievement of K outcomes using NTL and the presumed benefit of technical skills acquisition (P_r outcomes) from physical manipulation in TL. For distance education science classes, the traditional component of this approach typically utilizes lab kits. One might question the fidelity of such kits to true laboratory instruction, however, given that most current science laboratory lessons involve computer and technological mediation as part of their process. This was noted several years ago, prior to the present "blended" zeitgeist, by Ma and Nickerson (2006) when they stated:

> "While observing a hands-on laboratory, we noticed that hands-on labs are becoming increasingly mediated. For example, an experiment may involve measuring an output through a PC connected to the experimental apparatus. In such a case, the interactive quality of laboratory participation may not differ much, whether the student is collocated with the apparatus or not. Another way to say this it is that most laboratory environments may already involve an amalgam of hands-on, computer-mediated, and simulated tools" (p. 10).

So, take-home laboratory kits allow online students to actually work with discipline-specific equipment and supplies (TL) as well as interact with a NTL (i.e. a virtual lab).

In a recent study by the United States Department of Education, classes that implemented blended learning techniques were found to have produced a higher measure of outcomes than traditional techniques alone. These blended conditions often included additional learning time and instructional elements not received by students in control conditions, however, suggesting that the positive effects associated with blended learning should not necessarily be automatically attributed to the media (USDOE, 2010). Several other empirical studies have reported similar findings related to blended versus TL, though nearly all were based on assessment of the K outcome (Climent-Bellido, Martínez-Jiménez, Pones-Pedrajas, & Polo, 2003; Huppert, Lomask, & Lazarowitz, 2002; Kolloffel & de Jong, 2013; Olympiou & Zacharia, 2012; Zacharia et al., 2008). Likewise, studies have also produced data supportive of blended labs being more effective than NTL alone (Jaakkola, Nurmi, & Lehtinen, 2010; Jaakkola et al., 2011; Olympiou & Zacharia, 2012). Also, the sequence of traditional and non-traditional lab components in the laboratory procedure seems to make little difference. Toth et al. (2009) showed a slightly higher effectiveness when the NTL component preceded the TL component, whereas Carmichael, Chini, Gire, Rebello, & Puntambekar (2010) showed the opposite to be true. Chini, Madsen, Gire, Rebello, & Puntambekar (2012), on the other hand, found no significant difference. So a NTL component of some degree seems to be supportive of student achievement of learning outcomes, and the empirical evidence for a combination of TL and NTL being the most effective method of laboratory instruction is growing. Raineri (2001) supplemented a TL with a NTL (simulated) lab over a course of five years, which resulted in a 5% increase in the final exam scores and a much higher pass rate. Similar results were found by Ronen and Eliahu (2000) and McAteer et al. (1996). P_e data is also supportive of a blended approach. For example, Engum, Jeffries, & Fisher (2003) showed that students completing both a virtual and real catheter lab could adequately demonstrate the required skills, however, the students preferred performing the real lab against the virtual lab, thus suggesting that a combination of the two methodologies may enhance the students' satisfaction and skills acquisition level. The results of blended lab studies are mixed and no consensus exists yet regarding best practices, so this is a fascinating and important avenue of further research.

Appendix A

Table A.1
Studies coded by learning outcomes measured, evaluation instrument used, and lab modality outcome achievement.

Source	Outcomes measured							Evaluation instrument						Higher outcome achievement[a]	
	K	I	P	Pe(s)	Pe(i)	A	S	LR/WR	QZ/EX	SUR/QU	INT/OBS	PRAC	GR/GPA	TL	NTL
Akpan & Strayer, 2010	X			X					X	X					X
Arjamand & Khattak, 2013	X			X						X	X				X
Bakar & Zaman, 2007	X					X			X						X
Barbeau et al., 2013	X			X				X	X	X			X		X
Baser & Durmus, 2010	X								X						X
Braun & Kearns, 2008	X			X									X		(=)
Chan & Fok, 2009				X						X					X
Chini, Carmichael, Rebello, & Gire, 2010	X								X						X
Collier et al., 2012					X						X				X
Colorado DOE, 2012[b]	X												X	X	(=)
Dobson, 2009	X			X					X	X					(=)
Darrah, Humbert, Finstein, Simon, & Hopkins, 2014	X								X						(=)
Farrokhnia & Esmailpour, 2010	X		X						X			X			X
Finkelstein et al., 2005	X		X				X	X	X		X				X
Finkelstein et al., 2006	X		X				X	X	X						X
Flowers, 2011	X			X						X					X
Frederick, 2013	X		X	X				X	X	X		X			X
Gilman, 2006	X								X						X
Gorghiu et al., 2009	X				X					X	X			X	X
Hawkins & Phelps, 2013	X		X						X			X			(=)
Herga & Dinevski, 2012	X								X						X
Husmann et al., 2009	X			X					X				X		X
Jaakkola, Nurmi, & Lehtinen, 2005	X								X						X
Josephsen & Kristensen, 2006	X			X						X	X			X	
Klahr et al., 2007	X	X							X						(=)
Krippendorf & Lough, 2005	X			X					X						X
Lang, 2012	X	X	X	X		X	X	X		X					X
Lang et al., 2007	X								X						(=)
Morgil et al., 2008	X	X		X		X	X		X	X					X
Myneni et al., 2013	X								X						X
Nickerson et al., 2007	X			X					X	X					X
Olympiou & Zacharia, 2012	X								X						(=)
Olympiou, Zacharia, Papaevripidou, & Constantinou, 2008	X								X						(=)
Parker & Zimmerman, 2011	X		X						X			X		X	
Pyatt & Sims, 2007	X			X		X			X	X					X
Pyatt & Sims, 2012	X			X		X			X	X					X
Rajendran et al., 2010	X			X	X					X	X				X
Renken & Nunez, 2013	X								X						(=)
Scott, 2009	X			X	X					X			X	X	
Scoville & Buskirk, 2007	X			X					X						(=)
Sicker et al., 2005	X		X	X		X	X			X			X	X	
Srinivasan et al., 2006	X			X							X			X	
Stuckey & Stuckey, 2007				X						X				X	
Sun, Lin, & Yu, 2008	X			X					X	X					X
Taghavi & Colen, 2009	X			X					X	X					X
Tarekegn, 2009	X								X						X
Tatli & Ayas, 2012	X	X		X		X				X	X				X
Tatli & Ayas, 2013	X								X		X				X
Tuysuz, 2010	X								X						X
Tzafestas et al., 2006	X		X						X			X			X
Winn et al., 2006	X								X	X					X
Yang & Heh, 2007	X					X			X						X
Zacharia & Constantinou, 2008	X								X						(=)
Zacharia & Olympiou, 2011	X								X						(=)
Zacharia et al., 2012	X										X			X	(=)
Zacharia, 2007	X								X						X
Totals[c]	**52**	**4**	**9**	**25**	**4**	**8**	**5**	**5**	**39**	**22**	**10**	**5**	**6**	**9 (16%)**	**49 (89%)**

K = Knowledge & Understanding.
I = Inquiry Skills.
P = Practical Skills.
Pe(s) = student Perception.
Pe(i) = instructor Perception.
A = Analytical Skills.
S = Social & Scientific Communication.
LR/WR = Lab Report/Written Assignment.
QZ/EX = Quiz/Exam.
SURV/QU = Survey/Questionnaire.

INT/OBS = Interview/Observation.
PRACT = Lab Practical.
GR/GPA = Grade/G.P.A.
[a] An (=) indicates no difference in learning outcome achievement between NTL and TL.
[b] Evidence for higher or equal learning outcome achievement in both NTL and TL depending on discipline or outcome measured.
[c] Some studies supported higher achievement in both lab types, so total does not equal 100%.

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