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# A Review of Research on Technology-Assisted School Science Laboratories

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## ABSTRACT

Studies that incorporate technologies into school science laboratories have proliferated in the recent two decades. A total of 42 studies published from 1990 to 2011 that incorporated technologies to support school science laboratories are reviewed here. Simulations, microcomputer-based laboratories (MBLs), and virtual laboratories are commonly used to assist students in engaging in laboratory activities, followed by remote laboratories, databases, and other miscellaneous technologies. We report the demographics and characteristics of these technology-assisted laboratory studies and provide examples to illustrate how technologies have facilitated science learning in laboratories for different subjects and science domains, with various levels of student involvement and components of investigations. Major findings of the reviewed articles are summarized to understand the effects of applying technologies in school laboratories. Incorporation of technologies in school science laboratories has changed students' learning experiences in terms of the phenomena to be explored, their interactions with the natural phenomena or materials, and approaches to handling and making sense of data. Based on our findings, possible directions for future research and emerging instructional issues regarding technology-assisted laboratories are discussed.

## Keywords

Laboratory, Technology, Science learning, K-16

## Introduction

Laboratory learning constitutes an indispensable part of science education. Laboratories can motivate students, provoke active learning, and convey practice of science (Linn, 1997). Lunetta, Hofstein, and Clough (2007) defined school science laboratories (SSLs) as "learning experiences in which students interact with materials or with secondary sources of data to observe and understand the natural world" (p.394). For decades, SSLs have played a unique role in science curricula, providing opportunities for students to engage in investigation processes. Through experiencing scientific investigations, students might develop the abilities necessary to do scientific inquiry as well as an understanding of scientific inquiry (National Research Council [NRC], 2011).

The recent reform documents for K-12 and for post secondary education have stressed the importance of technology in SSLs. In these documents, the learning goals of having students gain knowledge and adequate skills for using technologies while practicing authentic science are explicitly stated (NRC, 2011; College Board, 2009). SSLs are expected to gradually equip students with the abilities to use technologies to gather, analyze, and transform data, as well as to create models, to communicate and to collaborate with others. Activities that reflect features of authentic inquiry are relatively complex and cognitively demanding (Chinn & Malhotra, 2002). Supports from technologies have been used to reduce cognitive load and overcome obstacles of learning in realistic experiments due to time, space, scale, and resources. A large-scale international survey, the Programme for International Student Assessment (PISA), administered by the Organization for Economic Co-operation and Development (OECD), has also begun to explore the possibilities of assessing students' skills in science using simulated laboratory experiments (OECD, 2010). Technology is playing an ever-increasing role in laboratory learning.

The incorporation of technologies in laboratory instruction may change not only the layout and supplementary resources, but also the nature of learning and teaching. Given the rapidity with which these technologies are being implemented in SSLs, a review of empirical studies is timely to understand how features of technologies can be matched with learners' needs and task demands as well as what the impacts on learning science in a technology-assisted laboratory are. Several reviews have been carried out to analyze and discuss the purposes and styles of SSLs, as well as the key elements that affect laboratory activities (e.g., Domin, 1999; Hofstein & Lunetta, 2004; Lunetta et al., 2007). Other reviews have in part examined the effects of technology on learning in science education or inquiry (e.g., Lee et al., 2011; Ma & Nickerson, 2006; Nelson & Ketelhut, 2007; Scalise, Timms, Moorjani, Clark, Holtermann, & Irvin, 2011). However, the combination of technology and SSLs has not been well documented in previous reviews. Thus, the purpose of this study was to conduct a systematic analysis of the general trend of applying technology to assist SSLs, including types of technology and their effectiveness. Our findings can be used as a springboard for the design and implementation of technology-assisted laboratories that support various aspects of scientific inquiry.

In the subsequent sections, we define the crucial concepts used in this study. Empirical studies that incorporate technologies to assist laboratory learning are analyzed using the narrative review method. Through the analyses, we hope to pinpoint some less explored areas in the current trends of technology-assisted laboratory studies. Alignments among characteristics of technologies, student involvement, and elements of scientific investigation as well as technology affordances for important learning outcomes are then discussed. Although technologies have shown some advantages in assisting students' learning of science in laboratories, which are presented in our findings, the incorporation of technologies may have changed students' experiences of the real-world phenomena and of scientific investigation in comparison to their experiences in traditional laboratories. For instance, observing a simulated representation of an unobservable phenomenon (e.g., the particulate nature of matter for phase changes) may have changed the nature of observations. For this reason, we conduct a critical reflection to redefine laboratory experiences in technology-assisted laboratories. Through an in-depth review, we hope to generate some new insights for the future design of research and instruction on using technologies in SSLs.

## Method

### Formation of an analytical framework

We formed a panel of ten experts in different areas of science and science education to construct the analytical framework (Chen et al., 2012). To address our first aim regarding the types of technologies used in SSLs, our first category included demographics of the studies and two characteristics of the technology-assisted laboratories: types of technologies such as simulations, MBLs, databases, virtual laboratories, remote laboratories, and others, and hardware devices involved such as desktop computers, handheld devices, sensors (e.g., motion detectors or thermometers), and others (Table 1). For types of technologies, free computer software, interactive videodiscs, or simple digital instruments such as pH meters were categorized as 'others'. For hardware devices, 'others' referred to equipment such as videodisc players, TV sets, or video cameras.

Next, we coded the length of intervention, levels of students' involvement in the technology-assisted laboratories, and the roles of technology in supporting components of scientific investigations. The length of intervention depicted the duration of the laboratory instruction in a study. The level of student involvement varied from teacher-centered to student-centered (Millar, Le Maréchal, & Tiberghien, 1999). In the light of the investigation web (Krajcik, Blumenfeld, Marx, Bass, Fredricks, & Soloway, 1998), seven components of scientific investigation were focused on (Table 1).

Finally, to explore what learning outcomes were assessed, we took the three major domains of the revised Bloom's Taxonomy of educational objectives (Anderson et al., 2001) including cognitive process, attitude, and psychomotor skills. Also, student learning in laboratories often involves gaining or exhibiting a combination of knowledge and skills such as problem-solving, scientific reasoning, or inquiry abilities. Therefore, we created the fourth domain, integrated skills. Other measured outcomes which did not belong to the aforementioned four domains were categorized as 'others' (Table 1). More details of the framework can be found in Chen et al. (2012).

*Table 1*. Coding scheme of the study

| Category | Sub-category | Associated codes |
|---|---|---|
| Basic information | Demographics | Science domains, subjects, sample sizes |
| | Characteristics of technology-assisted laboratory--Types of technologies | Simulations, MBLs, databases, virtual laboratories, remote laboratories, and others |
| | Characteristics of technology-assisted laboratory-- Hardware devices | Desktop computer, handheld devices, sensors, other equipment |
| Length of intervention | | One shot, 1-2 weeks, 3-8 weeks, one semester, unclear |
| Student involvement | | Teacher demonstration (demonstrated by the teacher; students observe)<br>Teacher demonstrates with assistance from students/student demonstrates under teacher's instruction<br>Student group work (practical work was carried out by students in small groups)<br>Student individual work (practical work was carried out by individual students) |
| Roles of technology in supporting components of investigations | | Messing about with phenomena<br>Finding information<br>Asking and refining questions<br>Planning and designing an investigation<br>Carrying out procedures<br>Making sense of data<br>Sharing findings |
| Measured outcomes | | Cognitive process, attitude, psychomotor skills, integrated, and others |

## Identifying papers for this review

Journal articles published from 1990 to 2011 in Science Citation Index and Social Science Citation Index journals were searched for using three sets of keywords: (1) Internet, Internet-based, computer, technology, web, web-based, online, or on-line, (2) laboratory or laboratories, and (3) science, physics, chemistry, biology, or geosciences. This process yielded 312 articles. Each abstract and title was read and screened individually by two panel members. An article was selected to the potential pool when it involved laboratory instruction in a science domain, incorporated technology in assisting learning, and provided empirical evidence. Articles that collected data of user satisfaction or involved exploratory or case studies were included as long as empirical data were reported. Articles in science domains such as physics, chemistry, biology, earth science and environmental science (including urban science), medical science (including nursing education), or which were interdisciplinary were included. Laboratories in engineering education for mastering software such as AUTOCAD, programming, or mechanistic design were excluded (n = 3), because the purpose of such laboratories deviates from our focus on science learning. In this stage, studies with vague descriptions regarding the selection criteria were kept to avoid missing important studies. The above screen process yielded 89 studies, including three that contained two sub-studies.

Using the same criteria, the panel members conducted the second screening by reading the entire articles. Discrepancies between the two panel members regarding the above screening process were discussed and resolved by consulting the opinions of a third panel member. Review articles (n = 12) or ones that did not contain empirical data were further excluded from the pool. Studies that did not involve utilization of technology (n = 12) or which did not relate to SSLs (n = 19) were also removed from the review pool. These articles were mainly in the fields of gene technology, computer laboratories, psychology laboratories, etc. Their context deviated from our view of technology-assisted SSLs. Finally, 39 articles (42 studies) entered the final review.

A narrative review rather than meta-analysis was selected as the review method because there were not many empirical studies applying experimental design for each technology except for simulations. Among the studies that used a control group, students' performances were assessed with various self-developed instruments including types of questions that students asked, score of concept maps or score of students' laboratory reports. It is difficult to compare effects of learning with a meta-analysis when various self-developed instruments are used. A narrative review seeks to comprehend the diversities and pluralities of understanding around scholarly research topics and is best suited for comprehensive topics (Collins & Fauser, 2005). The topic of our study is therefore appropriate for a narrative review. A narrative review is carried out by critically analyzing literature of a specific theme and drawing results and conclusions in a systematic way from a theoretical and contextual point of view. This is a rather qualitative approach that synthesizes in-depth information for what has been observed among the selected studies, contributed by the researchers' own experience and the existing theories (van Dinther, Dochy, & Segers, 2011).

### Analyzing procedure

Each of the 42 studies was independently analyzed and coded by two members of the panel based on the coding scheme in Table 1. Disagreements between the two examiners were resolved by revisiting and discussing specific segments of the article or by adding opinions of a third member. For studies that contained multiple sub-studies, we treated and coded each as a separate work. Information regarding experimental and control groups of a quasi-experimental design were also coded as different settings. Since one study may involve participants across different levels, address topics across subject areas, incorporate more than one type of technology, or compare effects of different types or designs of technology assisted laboratories, the frequency counts reported in the result tables may exceed the total number of reviewed articles.

## Results and discussion

### Demographics and characteristics of the selected studies

We first analyzed subjects, science domains, and use of hardware devices to illustrate the contextual information on types of technology-assisted laboratory activities.

#### *Subjects*

Most studies recruited undergraduate students (n = 25) or K-12 students (n = 20). Only one involved graduate students, and four incorporated preservice or inservice teachers. Waight and Abd-El-Khalick's (2011) study provided an interesting case by including five scientists, a computer programmer, and two science educators in their analysis and, therefore, was categorized as 'others'. The upper section of Table 2 shows cross tabulation between types of technologies and subjects. Simulations were applicable to students across K-16; whereas MBLs, virtual laboratories, and remote laboratories have addressed specific participant groups. MBLs were exclusively used at the K-12 level, while virtual laboratories and remote laboratories were mostly implemented with undergraduate students. Application of remote laboratories at the undergraduate level may reflect a growing need to foster collaborations and to share sophisticated instruments among universities (Scanlon, Colwell, Cooper, & di Paolo, 2004).

It should be noted that teacher education is an area that draws less attention in the selected studies. Teachers require both pedagogical content knowledge (PCK) and technological PCK (e.g., structuring students' interactions with a simulation, Eskrootchi & Oskrochi, 2010) in order to successfully implement laboratories infused with technology. Thus, more attention should be paid to teacher training to develop related pedagogies and increase practical skills in implementing various types of technology-assisted laboratories. More innovative designs for incorporating MBLs and virtual laboratories in teacher education and professional development may significantly enhance the quality of laboratory learning.

*Table 2*. Types of technologies applied for different subjects, science domains, and hardware devices

| Demographics and characteristics | Type of technologies | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Simulation | MBL | Data base | Virtual laboratory | Remote laboratory | Others | |
| Subjects | | | | | | | |
| K-12 | 6 | 8 | 1 | 1 | 0 | 4 | 20 |
| Undergraduate | 9 | 0 | 1 | 8 | 4 | 3 | 25 |
| Graduate | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Teachers | 2 | 0 | 1 | 1 | 0 | 0 | 4 |
| Others | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Science domains | | | | | | | |
| Biology | 2 | 2 | 2 | 1 | 1 | 2 | 10 |
| Chemistry | 4 | 2 | 0 | 4 | 1 | 4 | 15 |
| Physics | 8 | 4 | 0 | 2 | 2 | 2 | 18 |
| Earth science and environmental science | 2 | 0 | 0 | 0 | 0 | 0 | 2 |
| Medical science | 2 | 0 | 0 | 1 | 0 | 0 | 3 |
| Interdisciplinary | 0 | 1 | 0 | 1 | 0 | 0 | 2 |
| Hardware devices | | | | | | | |
| Desktop computers | 18 | 8 | 2 | 8 | 4 | 8 | 48 |
| Handheld devices (PDA, handheld computers) | 0 | 2 | 0 | 1 | 1 | 0 | 4 |
| Sensor | 0 | 8 | 0 | 0 | 0 | 2 | 10 |
| Other equipment | 2 | 0 | 0 | 1 | 1 | 2 | 6 |

### *Science domains*

The majority of the selected studies addressed areas of physics (n = 18), chemistry (n = 15), and biology (n = 10). Relatively few applications were in environmental and earth science or medical science (n = 2). We would like to point out that there are technology-supported curricula in environmental and earth science. These examples include projects built upon geographic information systems (GIS) (e.g., Bodzin, 2008) and curricula that enable students to perform an inquiry in a 3D immersive virtual environment such as "River City" (Ketelhut & Nelson, 2010). These projects allow students to gain experience of scientific practices and yet were not considered as laboratories in the traditional sense. This leads us to reconsider the question of what counts as a laboratory in the areas of earth science, environmental, and medical science, and whether there can be a definition of laboratory commonly shared across science domains (see further discussion of this issue in the Conclusions and a Critical Reflection section).

Table 2 also shows that biology laboratories often utilized simulations, MBLs, and databases, while chemistry laboratories often involved simulations and virtual laboratories. In physics, about half of the selected studies incorporated simulations, followed by MBLs. Overall, it seemed that a particular technology was more often used to serve a specific student group or to fit better with the nature of laboratory learning in some science domains than in others.

In general, the studies provided positive evidence for integrating technology into laboratories. Among the selected studies, a few factors that affect learning in technology-assisted laboratories were identified. Chang, Chen, Lin, and Sung (2008) indicated that students who are better at higher abstract reasoning benefit more from simulation-based physics learning. Also, students' prior knowledge and attitudes toward learning were found to affect the outcomes of a simulated undergraduate chemistry pre-laboratory (Winberg & Berg, 2007). Nevertheless, relatively few studies took into account participants' needs and characteristics (e.g., level of reasoning ability, proficiency of scientific process skills or technology skills). The lack of such information makes a systematic analysis impossible. Future studies can seek new applications of technologies in less explored science domains and teacher training. Meanwhile, learners' needs and characteristics as well as the nature of the content and laboratory learning are important factors that need to be taken into consideration when designing technology-assisted laboratories.

*Types of hardware devices*

Hardware devices could be desktop computers, handheld devices, and sensors (e.g., thermo sensors, or motion detectors as a part of the MBL tool kits)(Table 2). Other equipment included video cameras (Fiore & Ratti, 2007) and pre-made video-clips which were delivered with a videodisc player and/or a TV monitor (Brungardt & Zollman, 1995; Leonard, 1992) or were incorporated with a virtual laboratory (Kozma, 2003; Swan & O'Donnell, 2009). Desktop computers are the most common hardware device since simulations, virtual laboratories, or databases were installed on desktop computers. MBLs, to some extent, reflect a feature of mobility by using a combination of a sensor (n = 8) and handheld devices (n = 2) or by collecting data with sensors and further processing it on a desktop computer (n = 8). Although mobile phones, tablets, instant response systems, or interactive whiteboards are becoming increasingly popular in classrooms, we found no studies in our review that applied them to science laboratories. However, this might change in the near future since such devices have impacted different aspects of everyday life. Exploring innovative applications of technology and examining its effectiveness on learning in laboratories is a potential area for future research.

## Length of intervention, student involvement, and support for scientific investigation

Most studies designed a relatively short-term instruction of one shot (n = 5), one to two weeks (n = 14), or three to eight weeks (n = 15). Six studies implemented the laboratories for the entire semester, leaving two which did not specify their length of intervention. In the following section, we examine how the remaining two aspects were incorporated with different types of technologies.

*Student involvement*

Among the four levels of student involvement described by Millar et al. (1999), technologies were more frequently used in settings of students working in small groups (n = 23) or working individually (n = 18) than for teacher demonstration (n = 6)(Table 3). Although teacher demonstration with assistance from students or student demonstration under teachers' instruction was common in traditional laboratory activities, no technology was specifically utilized in this setting. Among the 19 studies using simulations, nine were carried out by students in small groups, six by individual students, and three by teacher demonstrations. Teacher demonstration often appears as a tutorial or as a preparation section with the purpose of familiarizing students with the program or system and to prepare them to work independently in the following experiments (e.g., Harris, Peck, Colton, Morris, Neto, & Kallio, 2009). The application of MBLs shows a similar trend of being used with small groups (n = 4) or individuals (n = 2). Half of the virtual laboratories were implemented for undergraduates to work individually. Remote laboratories were also often carried out by individual students. In sum, technology-integrated laboratories promote group work, whereas laboratories for undergraduates and in distance education settings are more likely to be designed for individuals.

*Table 3*. Cross tabulation of technologies and student involvement

| | Type of technologies | | | | | | |
|---|---|---|---|---|---|---|---|
| Level of student involvement | Simulation | MBL | Database | Virtual laboratory | Remote laboratory | Others | Total |
| Teacher demo | 3 | 0 | 0 | 1 | 1 | 1 | 6 |
| Teacher demo with assistance from students/Student demo under teacher's instruction | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Student group work | 9 | 4 | 1 | 4 | 1 | 4 | 23 |
| Student individual work | 6 | 2 | 0 | 4 | 2 | 4 | 18 |
| Unclear | 1 | 2 | 0 | 1 | 1 | 0 | 5 |

Questions remaining to be solved include how the various types of technologies facilitate or interfere with student-student, student-content, and/or student-technology interactions, and under what social conditions technology-assisted laboratories could have better learning outcomes. For example, Kelly and Crawford (1996) revealed how the use of MBLs influences learners' conversations about physics concepts. Manlove, Lazonder, and de Jong (2009) also indicated that, during a simulated inquiry activity, students who worked in a collaborative setting outperformed those who worked individually on their model quality and laboratory report, whereas task duration and specific tool use (e.g., notetaking, hints, and help seeking) did not differ between the two conditions. The above two studies were the few attempts to tackle the abovementioned issues that we observed among the selected studies. We urge that more studies investigate the social and conceptual interactions between learners and technologies.

### *Support of scientific investigation*

Table 4 reveals variations among types of technologies in terms of their roles in assisting different components of scientific investigations. In general, technologies were most frequently used to support investigations associated with messing about with phenomena (n = 29), carrying out procedures (n = 31), and making sense of data (n = 33), whereas sharing findings was the least emphasized component (n = 2). We also found that these technologies seemed to be applied for different functions. For instance, simulation was most likely used to aid students to mess about with phenomena (n = 12) and make sense of data (n = 12). MBLs were often used to assist in carrying out procedures (n = 8) and making sense of data (n = 8). Virtual and remote laboratories were designed to facilitate messing about with phenomena and carrying out procedures. Moreover, simulations, virtual laboratories, and remote laboratories are more applicable to supporting a broader range of scientific investigation processes, whereas MBLs were specifically used to aid students to mess about with phenomena, to carry out procedures, and to interpret findings. For example, Barros, Read, and Verdejo (2008) created a chemistry virtual laboratory composed of virtual laboratory scenarios, tools for remote experimentation, and electronic-interactive note-booking to support university students in all phases of an online inquiry about chemical substance identification.

*Table 4*. Roles of technologies in supporting components of scientific investigations

| Components of scientific investigations | Type of technologies | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Simula tion | MBL | Data base | Virtual laboratory | Remote laboratory | Others | |
| Messing about with phenomena | 12 | 3 | 1 | 7 | 3 | 3 | 29 |
| Finding information | 8 | 0 | 0 | 3 | 2 | 1 | 14 |
| Asking and refining questions | 6 | 0 | 0 | 2 | 2 | 1 | 11 |
| Planning and designing an investigation | 7 | 0 | 1 | 4 | 2 | 2 | 16 |
| Carrying out procedures | 7 | 8 | 0 | 7 | 4 | 5 | 31 |
| Making sense of data | 12 | 8 | 1 | 4 | 3 | 5 | 33 |
| Sharing findings | 0 | 0 | 0 | 1 | 1 | 0 | 2 |

The empirical results of the studies reveal distinct features of each technology in assisting laboratory learning. For instance, simulations and virtual laboratories have the advantage of representing a model, system, or process that cannot be easily observed in real life, such as phenomena in slow-motion or the motions of molecules which cannot be seen with the naked eye (Scalise et al., 2011). With this advantage, researchers with the purpose of helping students to gain in-depth qualitative understanding of the observed phenomena would favor simulations and virtual laboratories over other types of technology. Simulation-based laboratories make explicit the underpinning scientific theory, for instance, showing the moving electrons as a visual clue of the current flow when students build an electric circuit. Moreover, simulations could serve at the phase of carrying out procedures by simulating behaviors in which students can manipulate resistors, light bulbs, wires, and batteries as they would in the real world (Finkelstein et al., 2005; Jaakkola & Nurmi, 2008). Simulations can also be a powerful tool in helping students to develop a stronger sense of the data by giving them access to building a model of scientific phenomena and to realizing causal relationships among variables using visualization tools (e.g., Eskrootchi & Oskrochi, 2010). By the same token, MBLs will be an adequate resource if the main purpose of a laboratory activity is to aid students by simplifying procedures of data reading and logging and by processing data and displaying graphs real-time. By doing so, students would have spare time and cognitive resources to engage in conversations related to making meaning of graphs or to constructing alternative explanations (Russell, Lucas, & McRobbie, 2004).

We have observed a few examples starting to incorporate experiences of the simulated and real world phenomena or mixing remote and local resources to enhance conceptual learning and collaboration. Future research may pursue in-depth understanding of the nature of the technologies and of learning interactions during laboratory activities to design an effective technology-assisted laboratory and to explore innovative applications of the technologies in supporting students' laboratory learning. Furthermore, we found an inadequate alignment among the purposes and nature of scientific investigation processes and the actual learning outcomes in the reviewed articles. Nor did they address the degree of openness and freedom given to students in their design. These are crucial issues in laboratory learning and should have received more attention (Chen et al., 2012).

## Exploring technology affordances for important learning outcomes

In this section, we examine the effects and learning outcomes reported by the selected studies. Five types of learning outcomes were identified: cognitive processes, attitudes, psychomotor skills, integrated skills, and others.

Most studies reported students' cognitive processes as their only or major outcomes (Table 5). They revealed that technologies enhance students' cognitive processes, such as manipulating variables (Russell et al., 2004), visualizing data or scientific phenomena (e.g., Brungardt & Zollman, 1995; Jaakkola & Nurmi, 2008), and improving conceptual understandings (Cao & Bengu, 2000; Nakhleh & Krajcik, 1994). Among these studies, about half were supplemented with students' reports on their attitudes, specifically their satisfaction, interests, preferences regarding the technology used (e.g., Nickerson, Corter, Esche, & Chassapis, 2007), or their experience with the technology-assisted learning environment (e.g., Johnston & McAllister, 2008; Swan & O'Donnell, 2009). It should be noted that the focus was on students' feedback or perceptions, rather than their attitudes or motivations toward science. Finally, very few studies actually assessed psychomotor skills or integrated skills. The psychomotor skills that did come under investigation in these studies were visualization skills (Harris et al., 2009), graphing skills (Adams & Shrum, 1990) and operational skills (Finkelstein et al., 2005). With regard to integrated skills, a few studies were designed to support students in deploying or gaining a set of joint knowledge and skills to accomplish a complex task, such as acquiring reasoning skills (Barros et al., 2008) or inquiry abilities (Manlove et al., 2009). Rogers and Wild's (1996) study, which measured changes in the nature of classroom lessons and teaching style, was categorized as "others".

*Table 5*. Learning outcomes measured by studies with different types of technologies

| | Type of technologies | | | | | | |
|---|---|---|---|---|---|---|---|
| Outcome Measured | Simulation | MBL | Database | Virtual laboratory | Remote laboratory | Others | Total |
| Cognitive processes | 17 | 7 | 1 | 7 | 2 | 7 | 41 |
| Attitudes | 8 | 2 | 2 | 5 | 2 | 3 | 22 |
| Psychomotor skills | 0 | 0 | 1 | 1 | 1 | 1 | 4 |
| Integrated skills | 1 | 0 | 1 | 1 | 1 | 1 | 5 |
| Others | 0 | 2 | 1 | 0 | 0 | 1 | 4 |

A consistent conclusion of various studies was that combining simulations or virtual manipulations with physical laboratory activities creates a greater learning effect, such as gaining more conceptual understanding (e.g., Eskrootchi & Oskrochi, 2010; Jaakkola & Nurmi, 2008), posing more theoretical questions (Winberg & Berg, 2007), or making acceptable predictions and explanations (Zacharia & Anderson, 2003; Zacharia, Olympiou, & Papaevripidou, 2008) than learning in the simulation only and the laboratory only conditions. Simulations or virtual laboratories were often used in a pre-laboratory session to equip students with essential concepts and principles; the gained cognitive process in the preparatory session would then enhance learning and performance in the subsequent laboratory activities. However, there were counter findings regarding whether using simulations or virtual laboratories alone may (Finkelstein et al., 2005; Sun, Lin, & Yu, 2008) or may not (Eskrootchi & Oskrochi, 2010; Jaakkola & Nurmi, 2008) lead to significantly better performance than learning in the physical experiment-only condition. In addition to the cognitive outcomes, students reported preferences for the simulated or virtual laboratory learning environment (e.g., Eskrootchi & Oskrochi, 2010; Sun et al., 2008) and perceived the technologies as helpful (Swan & O'Donnell, 2009).

Considering the flexibility of simulations and virtual laboratories in supporting all aspects of scientific investigation discussed in the previous section, it is regrettable to find that only two studies have indeed examined the effects of the technologies on improving inquiry skills (Barros et al., 2008; Manlove et al., 2009). In terms of improvement in psychomotor skills, only two studies suggested that simulated equipment was effective in enhancing students' skills

(Finkelstein et al., 2005) or confidence in setting up and operating actual instruments (Finkelstein et al., 2005; Waller & Foster, 2000). Concerning effects of laboratories employing MBLs, all studies focused on investigating their benefits in terms of the students' cognitive processes, but none on the other objectives. MBLs improve students' conceptual understanding and the ability to interpret graphs (Adams & Shrum, 1990) because this technology provides multiple methods of graph display (Russell et al., 2004), affects the focus of students' observations (Nakhleh & Krajcik, 1993), and saves time for thinking, reflecting, and discussing (Rogers & Wild, 1996).

Remote laboratories and database studies were more diverse in terms of what learning outcomes were actually measured. Among the four studies using remote laboratories, findings have shown that students learned the content information (Barros et al., 2008; Nickerson et al., 2007) and rated the remote laboratories as equally effective as physical laboratories (Nickerson et al., 2007), with additional advantages in flexibility in class delivery, convenience in scheduling, and reliability of setup (Lemckert, 2003). Remote laboratories also show their potential in improving students' skills for observation and analysis of animal behaviors (Fiore & Ratti, 2007) and obtaining better integrated skills (Barros et al., 2008). Similarly, in the two database studies, Harris et al. (2009) used a variety of measures to provide evidence for the effectiveness of the learning environment. These measures included asking students to conduct investigations using the protein database and simulations, to visualize the protein structure, and to rate their preferences for the environment. However, the learning effect of database studies is inconclusive due to the small number of related studies. The results of the above analysis indicate that the majority of the simulation, virtual laboratory and MBL studies have provided evidence for whether and how these technologies promote students' cognitive processes and conceptual understanding. In comparison, how remote laboratories and databases can benefit learning outcomes and laboratory performance are less clear. More empirical research on using these technologies is encouraged.

When examining outcomes reported among the studies, most studies centered on the cognitive domain. Some studies looked at students' attitudes, mostly perceptions and reactions, toward the technology-assisted environment. Very few studies have actually measured psychomotor skills or integrated skills. Objectives such as changes in students' conversation or reasoning patterns, attitudes toward science, or skills of higher-order thinking (e.g., problem-solving ability), albeit crucial to laboratory learning, have nevertheless been neglected in the field. One possible reason could be the need for valid metrics to assess psychomotor or integrated skills such as visualization skills, graphing skills, operational skills and higher-order reasoning or inquiry skills in technology-assisted SSLs. As pointed out by Johnson, Levine, Smith, and Haywood (2010), new forms of technologies continue to emerge, bringing innovative interventions which aim to improve education and benefit student learning, but appropriate metrics to evaluate the educational value or impact often lag behind. There is a need for more studies on developing assessments focusing on psychomotor or integrated skills and establishing common criteria to evaluate the effectiveness of laboratory activities (Ma & Nickerson, 2006) to help reveal the variety of possible benefits that technology can bring to improving students' learning in science laboratories. Furthermore, more analyses of studies which match the nature and value of technology with the measured outcomes of the technology-assisted laboratories may help address this gap.

## Conclusions and a critical reflection

In the present study, we have reviewed empirical studies from the past two decades that incorporated technology-assisted laboratories. The characteristics of these studies are reported, supplemented with examples to illustrate how these technologies were used to aid laboratory learning at different science domains, subjects, student involvement, and phases of inquiry. Our results reveal that each technology has its distinct features and has different advantages or limitations in terms of supporting student involvement and learning of inquiry. We observed that most researchers employed technologies to support student group work or individual work and emphasized mainly cognitive outcomes. Developing assessments and criteria addressing affective aspects, psychomotor and integrated skills may generate more convincing and promising results beyond cognitive processes.

Articulating underlying interactions among technologies, the to-be-learned content, and the needs of learners may help advance our understanding and synthesize useful guidelines for designing effective SSLs. Based on our analytical framework and findings, we portray the key components, possible factors, and dynamic interactions occurring in the context of a technology-assisted laboratory in Figure 1. Learning and teaching in a technology-assisted laboratory is a complex phenomenon that involves features of technology, nature of content and laboratory instruction, as well as the characteristics of learners. The analytical framework allows us to examine this phenomenon from a holistic viewpoint. Resulting from our analyses, we have identified factors and interactions that have failed to be studied and which lack verification. These can be summarized as (1) how to match and/or infuse the features and value of technologies with the nature of content and laboratory learning, (2) how the technology facilitates or interferes with student-student, student-content, and/or student-technology interactions, and (3) how participants' needs and characteristics are assisted as well as under what conditions technology-assisted laboratories produce better learning outcomes.

One should understand that the components depicted in the above framework are interrelated, and that change in one component or interaction may lead to changes in the other parts of the framework. For this reason, when researchers and curriculum developers seek opportunities to match and integrate technologies with laboratory activities to improve learning, they need to be aware that the incorporation of technologies in SSLs may change students' experiences of the real-world phenomena and of scientific investigations. Physical and conceptual interactions between learners and the technology-mediated laboratory may differ in vital ways from those in a traditional laboratory. With this notion in mind, we conduct a critical reflection to reinterpret the definition of SSLs in the context of technology-assisted laboratories. We intend to discuss: (1) how the phenomena provided for students to explore in the technology-assisted laboratories vary from the "natural phenomena" demonstrated in a traditional laboratory, (2) how the way students observe or interact with the natural phenomena or materials by using tools or equipment changes, and (3) how their approaches to handling and making sense of data differ from those in traditional laboratories.

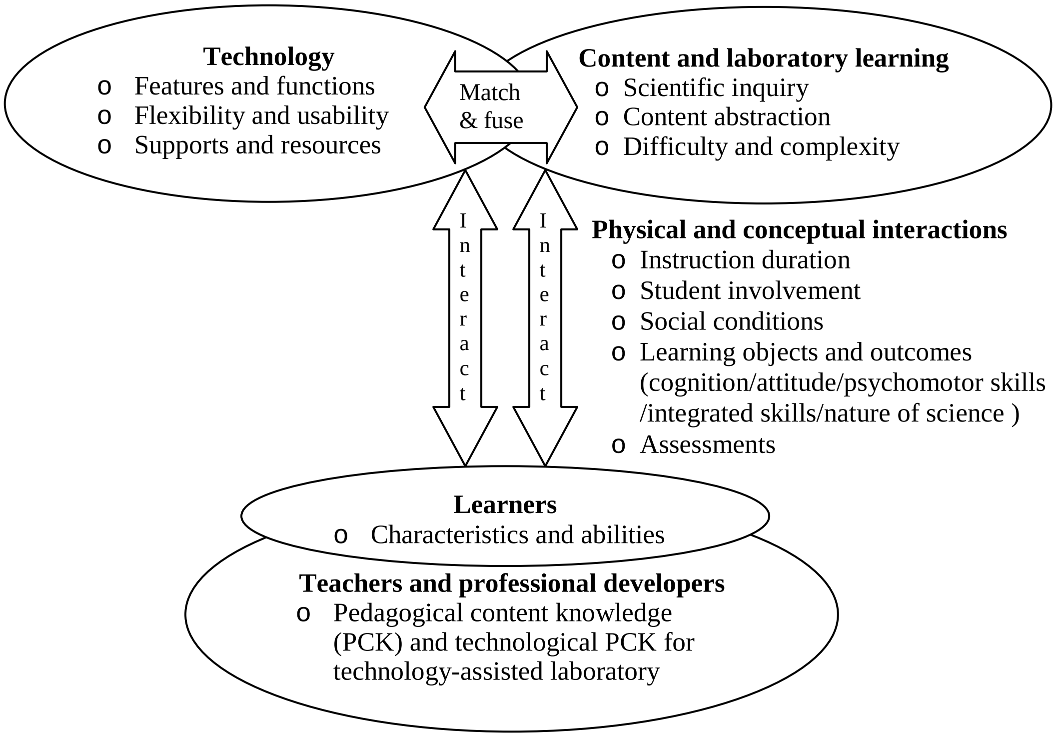

*Figure 1*. Factors and interactions for research on learning in technology-assisted SSLs

### What counts as phenomena

The availability of technologies in a SSL affords students the chance to investigate augmented, theorized, or inaccessible phenomena in comparison to the real world phenomena they explore in traditional laboratories. Augmented features such as virtual objects or simulated visual representations (e.g., moving electrons) may be added to a real world phenomenon to cue or enhance students' discussion and understanding during a scientific investigation (e.g., Finkelstein et al., 2005; Jaakkola & Nurmi, 2008). Likewise, students are able to simultaneously explore a real world phenomenon with augmented phenomena at the submicroscopic and symbolic levels (e.g., Kozma, 2003). Sometimes, learners may have difficulties in accessing core concepts when building theories or models of a target phenomenon. Engaging students in investigating a simplified version of theorized phenomena (e.g., Zacharia & Anderson, 2003), such as a friction-free situation, may help overcome these difficulties. When students investigate with these technology-mediated artifacts, some features, such as smells, might be unintentionally omitted from the real-world phenomena when they are delivered with remote or virtual laboratories.

Technology-enhanced phenomena may enrich and stretch students' experiences in SSLs. On balance, it may create new difficulties, arising from authenticity, fidelity, and credibility issues. For authenticity, we must consider whether activities and practices of inquiry embedded in the technology-enhanced environment align with those in the real world and science community (Klopfer, 2008) and how the mis-/alignment influences students' ability of solving real world problems in the long run. In terms of fidelity, we are concerned with whether the technology-mediated representation accurately and clearly portrays experts' mental models of the to-be-explored phenomena (Roschelle, 1996) and also what kinds of mental models students obtain from the technology-embedded learning experiences. Finally, we view credibility as the degree to which students believe something, such as observations or evidence, based on their experiences with the technology-enhanced phenomena (Tseng & Fogg, 1999). For instance, investigating theorized phenomena may leave students with no experience of dealing with errors in experiments (Chen, 2010). If students lose these senses in science laboratories, how may this influence their views regarding what counts as evidence? Few of the studies we reviewed discussed these new areas of student difficulties. It seems interesting for future studies to investigate students' notions of technology-mediated phenomena from the authenticity, fidelity and credibility aspects, as well as how their views affect their learning.

### Changes in interactions with the natural phenomena or materials

With the use of technologies, students nowadays can engage in scientific experiments without direct interactions with physical equipment or even without physical presence in the laboratory. Technology-mediated laboratories allow students to run repeatable operations (Sun et al., 2008) and accelerate the experiment with limited or no requirements of setting up the equipment by themselves (Zacharia et al., 2008) in comparison to a physical laboratory experiment. Finkelstein et al. (2005) argue that such laboratories may stress discovery rather than verification of science by allowing students to make mistakes without worrying about the consequences, to make changes in the setups and receive immediate feedback, and to repeat the experiments as many times as they desire. As science educators shift away from physical laboratory settings toward various technologies to explore new opportunities, future studies need to investigate what aspects of the physical experiences can or cannot be replaced with virtual or remote experiences, as well as to what extent this replacement or supplementation of physical manipulations influences students' attitudes toward science and laboratory activities and also their development of psychomotor skills.

### Difference in approaches to handling and making sense of data

The initial meaning of "making sense of data" proposed by Krajcik and colleagues (Krajcik et al., 1998) included processes of analyzing, transforming, and visualizing data, creating models, constructing scientific explanations, and also making conclusions. When technologies such as simulations or MBLs take the work of data-handling (e.g., data analysis, transformation, and visualization) from students, they can devote greater mental efforts to the remaining steps. The meaning of "making sense of data" may have to be redefined as model construction and development of explanations and conclusions since students now work with the "processed data" rather than starting from the directly-observed raw data.

In sum, the availability of technologies in a SSL has changed several aspects of learning during scientific investigation. Incorporation of technologies enriches and stretches the features of the to-be-explored phenomena; in the meantime, this change may have altered the way in which students conceptualize phenomena and their development of conceptual understanding. Students' sensory experiences and incidents about operating instruments or manipulating variables are physically changed when working in a technology-mediated laboratory. Working with processed data also alters the procedure of data handling and students' reallocation of time and mental efforts. Jointly, these intended or unintended changes in experiences of the technology-assisted SSL may, in turn, change the nature of learning with and about scientific inquiry. Effects of the aforementioned changes may show in students' learning outcomes in terms of conceptual understanding, attitudes, psychomotor and integrated skills, or views of nature of science. Based on our findings, we have suggested some possible directions for future research and have pinpointed some issues which have emerged when the incorporation of technologies has indeed changed the nature and process of a science laboratory as well as the nature of learning in it. Since technologies continuously and increasingly change and improve learning and activities in SSLs, we encourage more studies to explore opportunities for innovative integration of technologies with laboratories as well as to deepen our understanding regarding how students, technologies, and laboratory activities interact.

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