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WP4 and WP6:
Pilot 1 curriculum report

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Authors: Lysanne Post, Pengyue Guo, Nadira Saab & Wilfried Admiraal

Responsible partner: Leiden University

Statement of originality

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Summary

One promising way to cope with changing requirements from the labor market in the domain of Science, Technology, Engineering and Mathematics (STEM), but also to keep the field up to date, to start innovations and to advance the STEM domain as such is the use of student labs. In these labs, students work together in small groups imitating professional practice of design and technology workers. In the IoT Rapid Proto Labs project these student learning labs are the core elements. More insights are needed how to design a curriculum for student learning labs and how these can be implemented. Student labs should be designed as authentic productive learning environments based on three design principles: 1) Realistic, complex task situations, 2) Multidisciplinarity, and 3) Social interaction. IoT Rapid Proto Labs are examples of such a student labs, in which cross-border multidisciplinary teams of students, teachers (coaches), and practitioners jointly develop solutions to challenging IoT applications (Internet-connected objects), add value for enterprises, and strengthen the employability, creativity and career prospects of students. This general outline of the curriculum for pilot 1 was based on the findings of two literature reviews: one general one on project-based learning, which is one of the main characteristics of the pilot curriculum of the project and one on remote labs, which is referring to the nature of the student labs that are central in this curriculum.

In the first literature review, recent (2001 – 2017) empirical studies that focused on the measurement of the impact of Project-Based Learning (PBL) on student learning outcomes were investigated. Two categories of cognitive learning outcomes (i.e. knowledge and cognitive strategies), two categories of affective learning outcomes (i.e. perceptions of the benefits of PBL and perceptions of the experience of PBL), two categories of behavioral learning outcomes (i.e. skills and engagement), and artifact performance were extracted. Perceptions of PBL and engagement were the most and least measured learning outcomes, respectively. Four categories of measurement instruments were distinguished. namely questionnaires, rubrics/taxonomies, interviews, and tests. Both positive and negative impacts of PBL on student learning outcomes were revealed. Several other features of the studies reviewed and some implication for practice were also discussed.

The second literature review on remote labs in higher education examined the empirical research on learning benefits of such labs. The aim of this study was to investigate what kinds of learning outcomes were examined, how these effects were examined, and which findings these studies provided. Effects that were examined in the reviewed articles (k=23) concerned cognitive, behavioral, and affective learning outcomes. Overall, results showed positive findings with respect to all three types of learning outcomes: students gained conceptual knowledge, were engaged in the lab, and were satisfied with learning in a remote lab context. However, evaluation approaches of the learning outcomes were quite superficial, because examining the educational benefits of the remote labs was not the main focus of most articles. Future research should address this issue to provide more rigorous evidence about the possible benefits of remote labs on student learning in higher education.

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1. Introduction

This report on Pilot curriculum presents the general idea of the curriculum of the pilots in the IoT Proto Lab project and two literature reviews on similar educational designs: project-based curriculum and remote labs in higher education. In Chapter 1 we will provide an overview of design principles and ideas underlying the implementation of the pilot curriculum of the project. Three examples of student projects are provided, which will be added and revised during the project. These general design principles of the pilot curriculum are based on the findings of two literature reviews: one general one on project-based learning, which is one of the main characteristics of the pilot curriculum of the project and one on remote labs, which is referring to the nature of the student labs that are central in this curriculum. The first review (Chapter 2) is a literature review on project-based curricula in higher education and focuses on curricula in which students learn and work on an authentic project producing tangible output. These features make project-based curriculum different from problem-based curriculum in which solving a problem is the core feature. The second review (Chapter 3) is a literature review on remote labs in higher education, mostly technology and design education. As the review of Chapter 2 is focused on nature of the curriculum, the review in Chapter 3 is more about the constellation of learning and working together in virtual and face-to-face settings.

2. General outline of the curriculum

2.1 Introduction

Lack of skilled labor in the domain of Science, Technology, Engineering and Mathematics (STEM) is one of the main obstacles to EU economic growth in the coming years. In the period of 2015-2025, a growth in demand of STEM jobs of 8% is expected, compared to 3% for all occupations, leading to persistent shortages in terms of 700,000 job vacancies a year. University level education in the STEM domain is expected to provide future workers with a wide-range of technical skills and competences as well as an ability to understand and apply high level maths, science and other theory (Lucena, Downey, Jesiek, & Elber, 2008). Yet, at a time when there has been unprecedented attention around the need to increase training and recruitment, ‘Computer Science’ and ‘Engineering and Technology’ have the highest ‘subject-specific’ attrition rates in the UK university system (The Telegraph, 2017). Not only do the expected shortages create challenges for educational programs that prepare prospective professionals. Industries and businesses in the STEM domain form a dynamic, constantly changing field, which requires new skills from the professionals working in the field. These new skills are not only important to cope with these changing requirements, but also to keep the field up to date, to start innovations and to advance the domain as such.

These expected shortages and predicted changes means that prospective professionals in the STEM domain are required to develop a broad range of skills such as creativity, innovation skills, performance skills, critical thinking, problem-solving strategies, and self-regulation skills. As the range and complexity of these skills is so comprehensive that any one individual is unlikely to have them all, nor to have developed them all to the same high degree, prospective professionals should acquire communication, interaction and collaboration skills as well. All these skills are commonly referred to as 21Century Skills (21CS): cognitive, affective, motor and regulative skills that enable individuals and groups to face complex task situations effectively and efficiently. These 21CS are important to enable future workers to continuously adapt to and anticipate on what the profession, the labor market and society in general ask for.

Both these generic competences (i.e. 21 CS) and competences specific for the STEM domain (e.g., particular designing, programming and prototyping skills) require different educational setups compared to tradition teacher-centered ways of learning. One promising way and commonly used in design and technology studies is the use of student labs, which are small groups of student working together on solving authentic problems and producing solutions within a limited time period, imitating professional practice of design and technology workers. These student labs can provide an optimal learning environment to prepare students as future workers building on two main principles. First, these labs can be designed as authentic learning environments that simulate qualities of the – future- workplaces. Second, these labs can enhance particular student competences the labor market requires, in terms of both generic competences and competences specific for the STEM domain. Generally, three main types of student labs can be distinguished: 1) physical labs in which students learn and work together sharing the same location and time, 2) online labs in which students synchronously and a-synchronously learn and work together sharing the same virtual environment and 3) remote labs in which students control equipment in a lab from a distance. Often blends of the three main lab types are used. More insights are needed in what competences student labs in the STEM domain address and what the implications would be for the design of student labs.

2.2 Design principles of student learning labs in higher education

Developments in theories of effective learning and teaching reflect shifts from behaviorism to cognitivism to situationism (Day & Goldstone, 2012; Putnam & Borko, 2000). Lave (1988) challenged traditional views of learning and teaching by stating that new knowledge is constructed in the course of understanding and participating in new situations, a process generally referred to as "situated learning", with an emphasis of the social and interactive nature of learning. Taking a situated approach on teaching and learning helps to advance to design robust interventions in higher education practice. The creation of knowledge and skills is a continuous but not always linear process. It involves actively researching and experiencing reality as well as experimenting, which means building up experience goes with making errors. Skill formation is a social activity determined by the context and the way in which groups of people share knowledge and experiences. Learners build up knowledge that is linked to concrete applications, contexts and cultures. It requires the construction of practices and apprenticeship (Lave & Wenger, 1991).

In student learning labs, these perspectives of situated learning are combined. In these learning environments, the boundaries between formal and informal learning are fuzzy to engage students in meaningful, collaborative and authentic learning situations, where learners meet each other and workers in the field. Student learning labs require authentic productive learning environments shaped by:

1) *Realistic, complex task situations*, which give scope for the participant's initiative and exploration via divergent assignments, global guidelines and global criteria. The complexity requires interaction with other disciplines and between learners. These learning situations are 'hybrid', in which school-based learning and workplace experiences are closely connected.
2) *Multidisciplinarity*, as the real-life problems and challenges to cope with are not compartmentalized into clear-cut disciplines (Heijnen, 2015). Most suitable for the present project seems what they call *pragmatic interdisciplinarity*: an outcome centered approach that involves envisioning an effective and workable final product and back-filling through strategic selection of disciplinary inputs from the STEAM domain.
3) *Social interaction*, as learners need to apply and build up multiple skills and expertise, reinforced by mutual interaction and cooperation. The most important forms of creativity are joint cooperative activities of complex networks of skilled individuals (Sawyer, 2008) Social interaction is a crucial element of authentic productive learning environments, as it enables participants to operate as a learning community in which various forms of expertise, experiences and skills are shared (Wenger, 1998; 2009).

2.3 Implementation of student learning labs in higher education: IoT Rapid Proto Labs

IoT Rapid Proto labs are blended (virtual as well as real), user-driven, and authentic productive learning environments in which distributed multidisciplinary groups of five to then higher education

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students (from three European countries) collaborate on solving ill-structured problems. These students attend these blended multi-disciplinary learning and work environments as part of their bachelor or master program in the domains of Industrial design, Engineering and Technology. Throughout the discovery, design, develop and test process, student teams are continually supported by HEd teachers combining the roles of coach, guide and instructor. These labs are open environments, with flexible start and end dates, international virtual as well as local face-to-face interaction and collaboration, and dynamic boundaries between participants, and allowing both linear and nonlinear learning and work curves. The labs are also supported by a Project Arena (web-platform) which enables them to effectively collaborate on rapid-prototyping of IoT products/services. The Project Arena also stimulates the flow of knowledge and innovation between higher education, enterprises and other stakeholders. Each IoT Rapid Proto-Lab student-centered team will rapidly set-up, trial and test an innovative IoT solution for their SME/Start-up client. Technology regularly used in higher education support the learning and work processes of the lab participants, building on open-source learning platforms such as Moodle and open source collaborative writing tools, screen sharing, video conferencing, mind mapping and chat, as well as hard ware such as Whiteboards, tablets, smart phones and 3D printers.

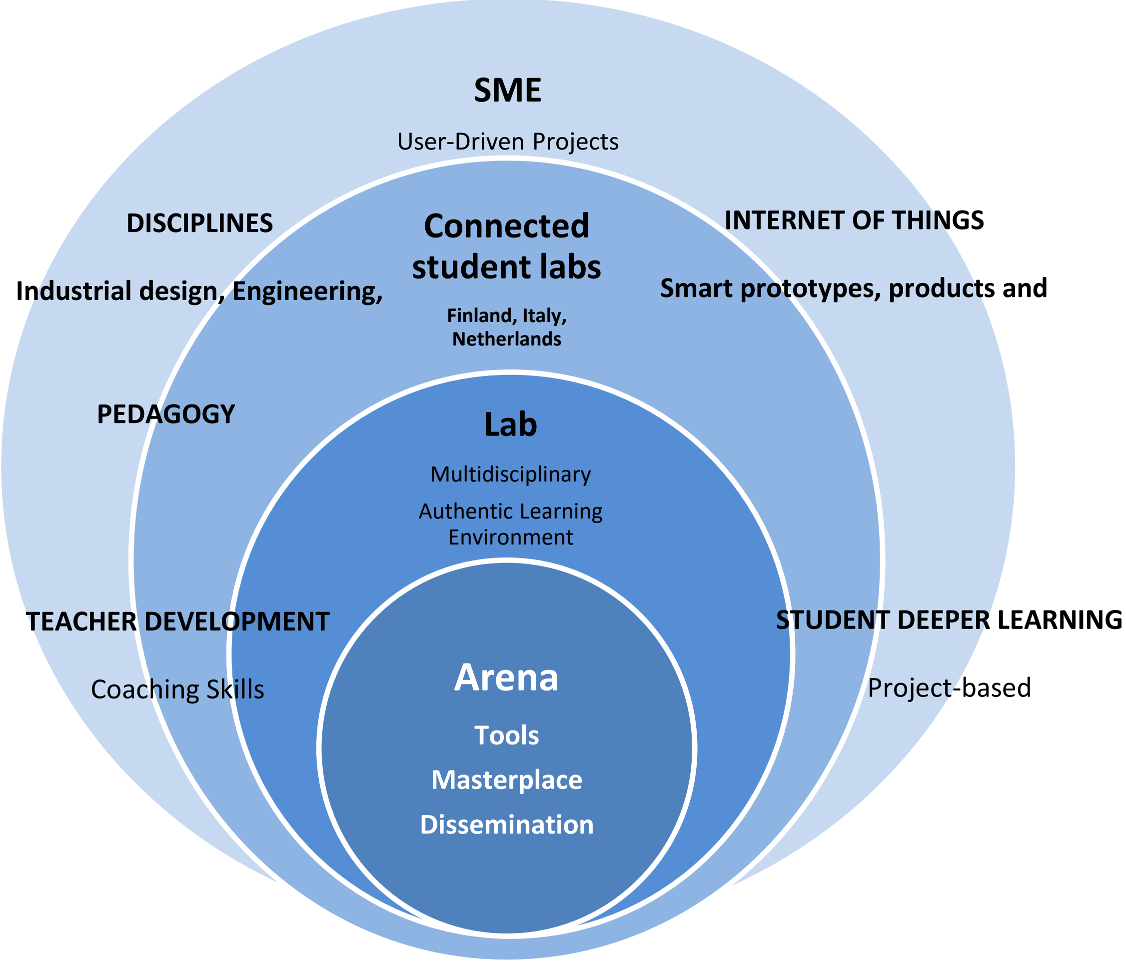

Figure 2.1. Design of IoT Rapid Proto Labs

IoT Rapid Proto Labs work on research challenges as well as assignment from SMEs or a network of SMEs. The research challenges deal with part-products, processes and tools that support and facilitate solutions for problems brought in by SMEs (e.g., embedded electronics, software efficiency, robotics control and vision). Through a newly developed portal, SMEs or networks of SMEs can provide two types of assignments:

1. Problem-oriented assignment: the SME presents problems they do not know how to solve and lab participants try to find a solution, and
2. Product-oriented assignment: the SME presents an idea or a product and the lab participants to address its development with an inter-disciplinary approach.

The labs can work on, for example, integration or adaptation of existing technologies, market and product analysis, industrial design, product design, and use experience. This combination of working on research challenges and authentic SME problems and issues create an innovative research-industry collaboration, with co-creation and interactions in communities of students and users. IoT Rapid Proto Labs, remotely networked, support participants with different skills and experiences to share competences and collaborate to find out IoT solutions (see Figure 2.1).

Three examples of authentic task for IoT Rapid Proto Labs are summarized in Table 2.1.

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Table 2.1. Three examples of authentic tasks of the IoT Rapid Proto Labs

1. Smart ski boots	2. Wearable devices for affective computing	3. Smart devices for wheelchair user well-being
A local company manufactures sport equipment and is particularly keen to innovate their line of ski boots. They are interested to innovate their product and add functionalities to attract customers. The company would like to develop a "smart boot" by adding sensing capabilities to it and provide the user with data analyzing of the skiing performance. In this case the project will cope with the search for existing solutions for sport motion analysis (e.g. inertial wearable sensors) and develop a solution which can be integrated within a ski boot and plan how it will be used. The project represents a real-life product development scenario and faces several multidisciplinary problems: • Product design: add-on for boot or integrate it; • Service design: just give the user sensors and data or provide an app and services to track/compare/share data; • Algorithms: which high-level information the system provide to the user; • Design: design of the product, ergonomic, usability, and • Business: existing solutions, market analysis, marketing approach.	Lab participants receive the assignment to study the development of a wearable device for implicit (no user interaction required) recognition of the user's activities and emotional state (affective computing). The device is worn by the user and it is accompanied by a smartphone app. There is a social component with friends connecting through social networks to compare activities and to exchange information/suggestions. The activities of the project include: • Study of requirements and technical specifications; • Development of hardware and software; • Data collection and development of algorithms for motion analysis; • Integration with smartphone app and backend for data storage and processing; • Integration with existing social solutions and development of a platform to share results/progress, and • Design of the product, design of its user experience, user acceptance evaluation.	Health and mobility are important pillars of well-being. Lab participants receive the assignment to design smart products and services for an internet-connected wheelchair using a domain-specific design platform. This platform is composed of standard hardware components only (Arduino, Raspberry Pi, Wi-Fi, Bluetooth, sensor) and communicates with the Data-Centric Design Hub via standards such as HTTP and MQTT. It comes with a step-by-step, get started guideline for designers without previous experience on IoT and a set of examples for sensing, processing and actuating. The platform supports students to inform, rapid-prototype and evaluate their design concepts in three phases: • Discovering: students receive a bare wheelchair to be transformed into a design platform learning about sensors, actuators and communication; • Experiencing: students use the wheelchair to collect and analyze data and try pre-set algorithms to control actuators, and • Designing: students design and prototype a product or service by extending or leveraging the design platform. For more information, see Bourgeois, Liu, Kortuem, and Lomas (2018).

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3 Review of project-based learning in higher education

3.1 Introduction

Although institutions of higher education have been trying to provide students with both hard skills, namely cognitive knowledge and professional skills (Vogler et al., 2018), and soft skills, such as problem solving (Schech, Kelton, Carati, & Kingsmill, 2017) and team working (Grotkowska, Wincenciak, & Gajderowicz, 2015), there still seems to be a huge gap, according to Learning for the 21st Century Report, between what students learn and what they will need to know in the future (as cited in Holmes, 2012). This gap might largely be caused by the prevailing, traditional, teacher-centered approach to education where students act as “the receptor of the information” (Alorda, Suenaga, & Pons, 2011, p. 1876). Thus, to reduce this gap, students need to be educated using a more student-directed system (Krajcik & Shin, 2014). One attractive way to operationalize student-centered learning is through project-based learning (PBL). However, there has been little knowledge of what students learn from PBL. Particularly, compared to the progressive development of PBL in K-12 education, the implementation of PBL in higher education has been left behind (J. S. Lee, Blackwell, Drake, & Moran, 2014). The current study will contribute to a better understanding of the effects of PBL on student learning in higher education.

3.2 Project-based learning

Project-based learning (PBL) refers to an inquiry-based instructional method that engages learners in knowledge construction by having them accomplish meaningful projects and develop real-world products (Brundiers & Wiek, 2013; Krajcik & Shin, 2014). Krajcik and Shin (2014) indicated six hallmarks of PBL, among which the creation of artifacts that solve authentic problems is most crucial, which distinguishes PBL from other student-centered pedagogies, for example, problem-based learning (Blumenfeld et al., 1991; Helle, Tynjälä, & Olkinuora, 2006). This requires learners to focus on the integration and application of prior knowledge rather than the acquisition of new knowledge (Prince & Felder, 2006). During PBL students usually work together to find solutions to authentic problems. Instructors and community members (e.g. clients), normally as facilitators, provide feedback and support for learners to assist their learning process, which is in line with the core idea of formative learning (Chanpet, Chomsuwan, & Murphy, 2018; Wiliam, 2011).

Several review studies have predominantly focused on PBL in post-secondary education. Helle et al. (2006) discussed both the practice of PBL and the impact of PBL on students’ learning. Regarding the practice, it was found that most of the studies reviewed were confined to course descriptions in terms of course scope, instructor requirements, and team size. As for the impact, the review found that only a few studies investigated the influence of PBL on student learning related to either cognitive (e.g. knowledge) or affective outcomes (e.g. motivation). In addition, several challenges that learners encountered during PBL – and a few solutions for some of these challenges – were revealed. In another study, Ralph (2015) reviewed fourteen studies that adopted PBL in STEM education and reported both positive and negative influences of PBL on student learning outcomes (e.g. knowledge and skills). Reis, Barbalho, and Zanette (2017) reviewed studies of PBL in engineering education by adopting bibliometrics (e.g. analysis of journals) and classifying qualitative data, such as research type and educational level, from the studies reviewed. Additionally, some benefits and difficulties of PBL were reported. However, this study had a significant limitation: the authors did not distinguish project-based learning (PjBL) from problem-based learning (PrBL), as they used the term "PBL" to indicate both pedagogical approaches.

3.3 Research questions

Although these reviews have mentioned student learning outcomes to a certain extent, there is no comprehensive and systematic picture of learning outcomes that can be connected to PBL. Therefore, the purpose of the present study is to examine the effects of PBL on student learning in tertiary education by building on the findings to the existing reviews. Specifically, the main research question for this review is as follows:

> "What are the impacts of PBL with regard to student learning in higher education?"

In addition, in order to thoroughly answer the main research question, the following research questions will be answered first:

(1) What types of student learning outcomes are measured in these studies?
(2) What types of instruments are adopted to measure these learning outcomes?

3.4 Method

3.4.1 Search

We used the federated search service provided by Leiden University Libraries which includes a variety of important Educational Sciences databases, such as Elsevier/ScienceDirect, ERIC, and Web of Science. The following search terms or combinations of terms and the Boolean parameters were used and presented in this way: Title contains *"project-based"* AND Title contains *learning OR curriculum OR curricula OR course OR courses* AND Any field contains *"higher education" OR undergraduate OR graduate OR "post-secondary" OR tertiary* AND Any field contains *outcome OR impact OR influence OR effectiveness*. The publication date of the articles was in a date range from 2001 to 2017. The year 2001 was considered as a cut-off point because we wanted to expand upon the findings of Helle et al. (2006) and focused on the literature that was published after the literature they included in their study. The material type of the results was Articles, and the language of these studies was English. In addition, all the articles were confined to peer-reviewed articles. In total, 249 articles were found (180 with full-text access).

3.4.2 Selection

Articles were further selected manually in two steps. In the first step, several selection criteria, i.e. (a) the studies had to be empirical and should provide original data; (b) the studies had to focus on student learning; (c) the process of PBL had to be conducted at the level of higher education; (d) the impact of PBL on student learning outcomes (i.e. cognitive, affective, and behavioral outcomes) had to be measured via measurement instruments were adopted. Therefore, non-empirical studies (e.g. Maida, 2011) and meta-analyses (e.g. Beddoes, Jesiek, & Borrego, 2010), studies which did not distinguish project-based learning from problem-based learning (e.g. Gavin, 2011), studies that did not focus on student learning (e.g. Habók & Nagy, 2016), studies conducted in non-tertiary contexts (e.g. Farrell & Hamed, 2016), studies focusing on the development of PBL curricula/activities/technologies (e.g. Gibson, 2003) and on the implementation/practices of PBL (e.g. Armacost & Lowe, 2003), and studies that measured the influence of tools/frameworks on PBL (e.g. Kim, Hong, Bonk, & Lim, 2011) should be excluded.

Specifically, the 180 full-text articles were filtered by title, abstract, and text. The 69 non-full-text articles were first filtered by title and abstract, which resulted in the exclusion of 48 studies. Then, the full-text of the remaining 21 articles was gained from other resources (e.g. open access databases), and filtered by text. Thus, there were 47 articles left for further selection. One of the authors, as the second independent rater, repeated the selection process and computed the inter-rater reliability. Ten percent of the full-text articles (i.e. 20 articles) were filtered by the second rater via using the same selection criteria as those of the first rater. The result showed that there was a 100% match between the two raters. Therefore, the inter-rater reliability for the present study was good.

In the second step, studies were filtered by focusing on whether they meet the key characteristic of PBL, namely the creation of artifacts. Seven articles were excluded due to the lack of clear reports of artifacts (e.g. Fernandes, 2014), Ultimately, a total of 40 articles were selected to be reviewed.

3.4.3 Analyses

After the selection, based on the content of these articles, we have set up a matrix in which the research design, the learning outcomes, the measurement instruments, the findings, and the limitations of all studies reviewed were presented. Based on this matrix, we examined the outcomes that were measured, the instruments that were used to measure these outcomes, and the impact and challenges that PBL had on student learning. The results are reported in the next section.

3.5 Results

Before addressing the three research questions, beginning with the two sub-questions and ending with the main question, information about the research design, the time point for data collection, and the type of learning is summarized in Table 3.1. As seen, most studies used a one-group design with a post-test only and are about learning in groups.

3.5.1 Types of learning outcomes

As shown in Table 3.1, both self-reported and externally measured learning outcomes were revealed in the 40 studies. These outcomes were divided into four categories, namely cognitive, affective, behavioral outcomes, and artifact performance.

Cognitive outcomes

Knowledge. Most studies interested in the evaluation of student subject knowledge (e.g. Luo & Wu, 2015). For example, biological knowledge, such as cloning and DNA isolation (Regassa & Morrison-Shetlar, 2009), psychological knowledge relevant to healthy living habits and pressure management (Lucas & Goodman, 2015), and technical knowledge related to space engineering (Rodríguez et al., 2015), were investigated.

Cognitive strategies. Several cognitive strategies adopted in PBL were assessed (e.g. Usher & Barak, 2017). For instance, seven strategies, including remembering, understanding, applying, analyzing, evaluating, creating, and straying off-topic, were adopted by students in Wu, Hou, Hwang, and Liu (2013). Similarly, learners in Stozhko, Bortnik, Mironova, Tchernysheva, and Podshivalova (2015) also used seven strategies that were divided into four levels, namely the lower level (identification), the basic level (knowledge and comprehension), the middle level (application and analysis), and the upper level (synthesis and evaluation). Both Heo, Lim, and Kim (2010) and Hou, Chang, and Sung (2007) identified students' five phases of knowledge construction, namely information sharing, disagreement detection, negotiation of meaning, modification of new ideas, and agreement statement.

Affective outcomes

Two types of students' perceptions, i.e. students' perceptions of the benefits and the experience of PBL consisted of affective outcomes. Specifically:

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Table 3.1. Studies coded by research design and data collection time point, type of learning and artifacts, learning outcomes, and measurement instruments.

Source	Research design			Data collection time point			Type of learning		Type of artifacts			Cognitive outcomes		Affective outcomes		Behavioral outcomes		Artifact performance	Measurement instruments			
	One-group	Comparative-group		Pre	During	Post	G	Ind	P	D	M	K	CS	Pe(b)	Pe(e)	S	E		Q	R/T*	I	T*
		Comparative	Control																			
1. Balve & Albert, 2015	x					x	x		x						x				x			
2. Berbegal-Mirabent, Gil-Doménech, & Alegre (2017)	x					x	x			x					x	x*			x	x		
3. Biasutti & EL-Deghaidy, 2015	x					x	x				x		x						x			
4. Botha, 2010	x					x	x		x					x	x				x			
5. Brassler & Dettmers, 2017			x	x		x	x			NC						x			x			
6. Brennan, Hugo, & Gu, 2013	x			x		x	x		x					x					x			
7. Chua, 2014		x				x	x		x			x*			x	x*		x*	x	x		x
8. Chua, Yang, & Leo, 2014		x				x	x		x			x*			x	x*		x*	x	x		x
9. Cudney & Kanigolla, 2014	x					x	x		x			x	x				x		x			
10. Dauletova, 2014	x					x	x			x				x					x			

Source	Research design			Data collection time point			Type of learning		Type of artifacts			Cognitive outcomes		Affective outcomes		Behavioral outcomes		Artifact performance	Measurement instruments			
	One-group	Comparative-group		Pre	During	Post	G	Ind	P	D	M	K	CS	Pe(b)	Pe(e)	S	E		Q	R/T*	I	T*
		Comparative	Control																			
11. Dehdashti, Mehralizadeh, & Kashani, 2013	x					x	x			x				x	x				x		x	
12. Dzan, Chung, Lou, & Tsai, 2013	x					x	x		x						x				x			
13. Frank & Barzilai, 2004	x				x	x	x		x	x	x			x	x			x*	x	x	x	
14. García, 2016	x			x		x	x			x		x							x			
15. Heo, Lim, & Kim, 2010	x					x	x			x			x*							x		
16. Hogue, Kapralos, & Desjardins, 2011	x					x	x				x				x				x			
17. Hou, Chang, & Sung (2007)	x					x		x		x			x*							x		
18. Katsanos, Tselios, Tsakoumis, & Avouris, 2012			x	x		x	x			x		x							x			
19. Kettanun, 2015	x			x		x	NC			x		x*	x			x				x	x	
20. Lee, 2015	x					x	x		x						x			x*	x	x		

Source	Research design			Data collection time point			Type of learning		Type of artifacts			Cognitive outcomes		Affective outcomes		Behavioral outcomes		Artifact performance	Measurement instruments			
	One-group	Comparative-group		Pre	During	Post	G	Ind	P	D	M	K	CS	Pe(b)	Pe(e)	S	E		Q	R/T*	I	T*
		Comparative	Control																			
21. Lucas & Goodman, 2015	x			x		x	x			x		x		x					x			
22. Luo & Wu, 2015	x			x		x	x			x		x							x			
23. Musa, Mufti, Latiff, & Amin, 2011	x					x	x			x				x	x				x			
24. Ngai, 2007	x					x	x			x	x				x				x			
25. Papastergiou, 2005	x			x		x	x				x			x				x*	x	x		
26. Raycheva, Angelova, & Vodenova, 2017	x					x	x			NC					x				x			
27. Regassa & Morrison-Shetlar, 2009	x			x		x	x			x		x*		x							x	x
28. Rodríguez et al., 2015			x	x		x	x			NC		x			x	x			x			
29. Sababha, Alqudah, Abualbasal, & AlQaralleh, 2016	x					x	x		x	x				x					x			

Source	Research design			Data collection time point			Type of learning		Type of artifacts			Cognitive outcomes		Affective outcomes		Behavioral outcomes		Artifact performance	Measurement instruments			
	One-group	Comparative-group																				
		Comparative	Control	Pre	During	Post	G	Ind	P	D	M	K	CS	Pe(b)	Pe(e)	S	E		Q	R/T*	I	T*
30. Seo, Templeton, & Pellegrino, 2008	x			x		x	NC				x	x		x					x			
31. Stefanou, Stolk, Prince, Chen, & Lord, 2013			x	x	x	x	x			NC			x		x				x			
32. Stozhko, Bortnik, Mironova, Tchernysheva, & Podshivalova, 2015			x			x	NC				x		x*							x		
33. Thomas & MacGregor, 2005	x					x	x				x				x			x*	x	x		
34. Torres, Sriraman, & Ortiz, 2017			x	x		x	x			x		x*						x*	x	x		
35. Tseng, Chang, Lou, & Chen, 2013	x			x		x	x		x						x				x		x	
36. Usher & Barak, 2017		x				x	x			x			x*					x*		x		

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Source	Research design			Data collection time point			Type of learning		Type of artifacts			Cognitive outcomes		Affective outcomes		Behavioral outcomes		Artifact performance	Measurement instruments			
	One-group	Comparative-group		Pre	During	Post	G	Ind	P	D	M	K	CS	Pe(b)	Pe(e)	S	E		Q	R/T*	I	T*
		Comparative	Control																			
37. Wu, Hou, Hwang, & Liu, 2013			x		x		x			x			x*							x		
38. Wurdinger & Qureshi, 2015	x			x		x		x		x						x			x		x	
39. Yam & Rossini, 2010		x			x			x		x					x				x			
40. Zhang, Peng, & Hung, 2009	x				x	x	x			NC					x						x	
Totals	29	4	7	15	5	38	34	3	11	20	8	12	9	11	19	7	1	8	32	14	7	3

Note: G = Group; Ind = Individual; P = Physical objects; D = Documents; M = Multimedia; K = Knowledge; CS = Cognitive Strategies; Pe(b) = Perceptions of the benefits of PBL; Pe(e) = Perceptions of the experience of PBL; S = Skills; E = Engagement; Q = Questionnaire; R/T = Rubric/Taxonomy; I = Interview; T = Test

NC = Not clear

* indicates externally measured learning outcomes and instruments; the rest indicates self-reported learning outcomes and instruments

Perceptions of benefits. Evaluations by students about what they obtained from PBL were investigated. For example, learners reported the influence of PBL on their understanding of subject key concepts and interests in learning electrical engineering (Sababha, Alqudah, Abualbasal, & AlQaralleh, 2016). Some aspects of students' self- efficacy, such as facets regarding technology use and subject knowledge, were impacted by PBL (Brennan, Hugo, & Gu, 2013; Seo, Templeton, & Pellegrino, 2008).

Perceptions of experience. Students' various feelings about PBL were investigated. For example, students' satisfaction with PBL (Balve & Albert, 2015; Dehdashti, Mehralizadeh, & Kashani, 2013) and the ir attitude towards PBL (Y. M. Lee, 2015; Musa, Mufti, Latiff, & Amin, 2011; Raycheva, Angelova, & Vodenova, 2017) were investigated. Whether PBL supports learners' autonomy during activities was also explored (Stefanou, Stolk, Prince, Chen, & Lord, 2013). In addition, several studies reported students' comparisons between PBL and other learning patterns (Frank & Barzilai, 2004; Ngai, 2007; Zhang, Peng, & Hung, 2009).

Behavioral outcomes

Skills. Several studies focused on students' problem-solving skills (e.g. Chua, 2014; Chua, Yang, & Leo, 2014). For example, Brassler and Dettmers (2017) emphasized three points in problem solving: (a) considering and applying different views; (b) re-considering the strategies used; and (c) adopting discipline-based methods. Other skills, such as team working (Rodríguez et al., 2015) and social skills (Kettanun, 2015), were also investigated.

Engagement. Learners' perceived engagement was reported in Cudney and Kanigolla (2014). Three aspects of students' engagement, i.e. the level of their general involvement in the semester project, the degree of their participation in class discussions, and whether they applied the course concepts to practice were investigated.

Artifact performance

Three types of artifacts (see Table 3.1), i.e. physical objects, documents, and multimedia were most popular in the studies analyzed. A number of grading points were created to evaluate the performance of these products. For example, the dryers that students developed were assessed by criteria like original design and product quality (Chua, 2014; Chua et al., 2014). Accuracy, completeness, and neatness are three important factors when a bid report was evaluated (Torres, Sriraman, & Ortiz, 2017). Five aspects of website creation, including topic, content and aesthetics, pedagogy, technology, and usability, were evaluated in Papastergiou (2005).

3.5.2 Measurement instruments

Four categories of instruments (both self-reported and externally measured) were used to measure student learning outcomes (see Table 3.1). The most frequently used instruments were questionnaires, by which students' perceptions was primarily assessed. Different types of questionnaires, such as Likert-type scales and qualitative questionnaires with open-ended questions, were adopted to measure various learning outcomes (e.g. skills in Brassler & Dettmers, 2017; knowledge in García, 2016).

Rubrics and taxonomies are the second most frequently used tools, by which product quality (e.g. Thomas & MacGregor, 2005) and student cognitive strategies (e.g. Heo et al., 2010) were mostly assessed, respectively. For instance, grading rubrics designed by instructors who had research experience was adopted to evaluate the dryers that student made (Chua, 2014; Chua et al., 2014). A

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coding scheme was adopted to analyze the online interactions between learners in Hou et al. (2007). Regarding the taxonomy, although both Stozhko et al. (2015) and Wu et al. (2013) used the revised Bloom's Taxonomy to assess students' cognitive strategies, the authors used different operationalization of this taxonomy.

Interviews were frequently used to measure affective outcomes. For example, semi-structured interviews were adopted to assess learners' attitudes towards STEM subject during PBL (Tseng, Chang, Lou, & Chen, 2013) and feelings of autonomy (Zhang et al., 2009). In addition, students' cognitive processes and interpersonal skills were revealed by unstructured interviews (Kettanun, 2015).

Tests were adopted to measure students' knowledge and skills. Students' self-directed knowledge and problem-solving skills were measured by written tests with knowledge-based, application-based, analysis-based, and synthesis-based questions (Chua, 2014; Chua et al., 2014). In Regassa and Morrison-Shetlar (2009), concepts of biology were examined with a test with three multiple-choice and seven open questions.

3.5.3 Impacts of project-based learning

In this section, research findings in the studies reviewed will be synthesized and analyzed to answer the main research question.

Impact on cognitive outcomes

Knowledge. Overall, PBL promoted the development of student knowledge (e.g. Chua, 2014; Chua et al., 2014; Katsanos, Tselios, Tsakoumis, & Avouris, 2012; Torres et al., 2017). For example, Seo et al. (2008) reported significant improvement of preservice teachers' subject knowledge and knowledge related to technology use after a multimedia-assisted PBL course. After developing eight multimedia products, such as teaching websites and online courses, a pre- and post- survey in a one-group-only design revealed: (a) all forty-two learners agreed that they had a high-level grasp of subject matter; (b) there was an obvious increase in the number of participants (from 56% to 97%) who made significant progress in organizing the relationships between different areas of subject knowledge (e.g. facts and concepts); (c) 82% (post) rather than 59% (pre) learners felt they had increased their knowledge of how to conduct inquiries and generate new ideas in their subject domain. In addition, students improved their proficiency not only with the software they used frequently but also with the programs they were less familiar with.

Cognitive Strategies. Students' cognitive development via PBL was reported (e.g. Heo et al., 2010; Hou et al., 2007; Stozhko et al., 2015; Usher & Barak, 2017). For instance, the effectiveness of PjBL and PrBL courses on the cognitive learning strategies that students used was compared in Stefanou et al. (2013). The most essential distinction between these two types of courses was learning goals. In PrBL courses, acquiring new content knowledge was the most important aim, while PjBL courses aimed at integrating and applying students' prior knowledge. Thus, the analytical process instead of specific knowledge seems to be emphasized in PjBL. A self-reported survey revealed that students who were involved in PjBL had higher levels of elaboration, critical thinking, and metacognition than did their PrBL counterparts.

Impact on affective outcomes

Perceptions of benefits. Overall, students perceived that PBL promoted their learning (e.g. Papastergiou, 2005; Seo et al., 2008). For example, regarding to personal well-being, it was found that while students did not feel that the quality of their interrelationships with others had improved, they improved in their self-evaluation and in having a clear sense of a meaningful life by taking the PBL

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course (Lucas & Goodman, 2015).

Perceptions of experience. Generally, learners were satisfied with PBL and had good learning experience (Chua, 2014; Chua et al., 2014; Dzan, Chung, Lou, & Tsai, 2013; Raycheva et al., 2017). For instance, students realized the importance of STEM subjects and significantly improved their attitudes towards it after the PBL course (Tseng et al., 2013). They also felt more support from teachers to encourage their independent thinking during PBL (Stefanou et al., 2013). However, it was also found that students encountered difficulties during PBL. The most frequent complaint about PBL was that it required learners to spend much more time on learning than they were used to (Zhang et al., 2009) because, for example, a lot of time was wasted in the beginning as students had no idea how to start (Frank & Barzilai, 2004). This situation resulted in a heavy workload (Yam & Rossini, 2010), pressure (Y. M. Lee, 2015), and even conflicts among group members (Dauletova, 2014) due to students' unfamiliarity with and anxiety about this learning approach (Chua et al., 2014).

Impact on behavioral outcomes

Skills. Although some skills improved after PBL (Chua, 2014; Chua et al., 2014), no positive influence of PBL was found in terms of interdisciplinary skills (Brassler & Dettmers, 2017). The authors compared the effectiveness of project-based learning (PjBL) and problem-based learning (PrBL) courses on students' interdisciplinary skills. All the courses examined in this study were strictly selected via important elements, such as course duration, driving questions, educational practices, the role of instructors, and learning outcomes. By adopting a pretest-posttest control group design with self-reported scales, the study found that PrBL rather than PjBL significantly improved interdisciplinary skills. One possible explanation for this finding is that there was a big difference between the disciplines (i.e. social sciences and natural sciences) of PjBL, a difference that did not exist in PrBL.

Engagement. It was found that PBL had a positive impact on students' learning engagement (Cudney & Kanigolla, 2014). In general, learners reported that they took an active part in PBL activities and had a high level of participation in class discussions.

Impact on artifact performance.

The quality of the products developed by learners was improved through PBL (e.g. Chua, 2014; Papastergiou, 2005; Torres et al., 2017). For instance, Chua et al. (2014) compared the effectiveness of conventional PBL and enhanced PBL on the performance of the dryers made by learners during an engineering course. The difference in the settings of these two groups of PBL was that the enhanced PBL had several innovative interventions, such as analogies and mind-maps, which facilitated students' involvement in active learning. Data analysis revealed that most participants (83.3%) in the enhanced PBL groups gained A and B level grades while only 50% of students of the conventional PBL groups achieved these grades. Moreover, compared to the conventional PBL groups, dryers developed by the enhanced PBL groups were more innovative and produced better-dried samples in less drying time.

3.6 Discussion

With respect to the learning outcomes, most studies addressed students' perceived benefits and experience of PBL, and almost no studies explored their engagement. Regarding the measurement instruments, most studies adopted questionnaires. Overall, PBL has positive impacts on all learning outcomes measured. However, there were also difficulties of PBL reported in terms of students' learning experience.

We observed that students were expected to develop diverse abilities in only one course (e.g. Dauletova, 2014; Dehdashti et al., 2013). For example, Frank and Barzilai (2004) were interested in many outcomes, such as interdisciplinary knowledge, decision-making, communication skills,

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motivation, self-esteem, and sense of responsibility. However, it is not practicable to focus on multiple aims at one time (Helle et al., 2006). This may result in issues like the lack of a (clear) definition of learning outcomes (e.g. Lee, 2015; Rodríguez et al., 2015; Wurdinger & Qureshi, 2015). Therefore, we suggest that teachers/course designers focus on the most significant goal of PBL as well as the competence that learners need to improve.

Furthermore, we observed that formative assessment was less used, compared to summative assessment, as in most studies the data was collected after the course. Nevertheless, during PBL students ask for teachers' feedback when they encounter problems and use it to improve their co-creation of artifacts (Chanpet et al., 2018), which consistent with the core idea of formative assessment. In other words, formative assessment could be a built-in part of PBL (Gülbahar & Tinmaz, 2006). In addition, the positive association between formative assessment and student achievement has been reported (e.g. Wiliam, Lee, Harrison, & Black, 2004). Thus, we suggest that teachers adopt more formative assessment as it might improve students' learning.

Last, although it is the artifact development that differentiates PBL from other forms of learning, the evaluation of products is less of a concern in the studies analyzed. The final product is of importance because it is the concentrated expression of various competence that students may develop during PBL. Thus, if we want to evaluate PBL which features the characteristic of making artifacts, then the assessment of artifacts should be included.

Several limitations were found in the studies analyzed, which makes it debatable whether the conclusions of some articles were credible. Some studies reported students' higher satisfaction with PBL compared to traditional learning environments. However, the research design in those studies did not support their findings because only one-group design was adopted. Secondly, some measurement instruments were weak (e.g. Balve & Albert, 2015; Hogue, Kapralos, & Desjardins, 2011). For example, a three-point Likert scale without the report of reliability and validity was used in Dehdashti et al. (2013). In addition, the quantitative analyses in some studies (e.g. Dauletova, 2014; Musa et al., 2011; Sababha et al., 2016) were limited to descriptive statistics. As for the qualitative analyses, a number of studies reviewed (e.g. Kettanun, 2015; Regassa & Morrison-Shetlar, 2009; Zhang et al., 2009) lacked quality checks or guarantees such as an audit procedure (Akkerman, Admiraal, Brekelmans, & Oost, 2008).

3.7 Conclusion

The aim of this study was to investigate the effects of PBL on students' learning in higher education. More findings were built on to previous reviews revealing a comprehensive image of learning outcomes and the corresponding measurement instruments adopted. In addition, the impacts of PBL on learners' final artifacts were newly reported. In summary, the present study provides a clear description of the effects of PBL on students' learning in higher education by revealing the types of learning outcomes measured and the instruments used to measure them. The limitations of the existing PBL studies were discussed and how future research should address these concerns.

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4. Review of effects of remote labs on student learning in higher education

4.1 Introduction

In the last fifteen years, remote labs have become more and more common practice, especially in science and engineering education (Brinson, 2015; Ku, Ahfock, & Yusaf, 2011; Nedic, Machotka, & Nafalski, 2003). Likewise, scientific research on remote labs in these disciplines has increased dramatically since 2005 (Heradio et al., 2016b). In the context of higher education, remote labs are defined as remote control of a physical lab at a university. Students literally control from a distance equipment that is stationed in a physical lab. Benefits of remote labs over physical labs are the lower costs, the availability (24/7), the accessibility (e.g. for student in a wheelchair; Grout, 2015), and the possibility to remotely collaborate and cooperate with peers, even abroad (Alamo et al., 2002; Auer, Garbi Zutin, Maier, & Hardison, 2009; Henry, 2000; Heradio et al., 2016a). Remote labs can be beneficial to students, teachers, and institutions in higher education. Students can arrange their learning process to fit their needs as they can do their lab work anywhere and anytime, which can create a feeling of autonomy that contributes to motivation (Deci & Ryan, 1985). Teachers can instruct, guide, and help students from a distance. This way they can simultaneously supervise different groups of students at the same time, which is more efficient than supervising groups of students in the physical lab one by one. For universities, the financial aspect is very relevant. As said described before, education through remote labs is more efficient and therefore less expensive than education in physical labs. This high efficiency is achieved by tight scheduling (the minute one student logs out, the other can log in), shorter time slots (there is no setup and tear down time of the equipment), and non-stop scheduling (students can access the lab 24/7). Although there are many publications on remote labs, most of them are merely technical (e.g. how to set up a remote lab or specific examples of remote labs; see Almarshoud, 2011 for a review). In contrast, scientific studies on the educational effectiveness of remote labs are far less prevalent.

4.2 The educational value of remote labs

A few review studies have been performed to evaluate the educational effectiveness of remote labs (e.g. Brinson, 2015; Ma & Nickerson, 2006). Ma and Nickerson (2006) found that it was difficult to compare the few existing papers on remote labs and hands-on labs, because studies emphasize different aspects. Hands-on labs mostly focus on design skills, while remote labs are argued by others to be effective for conceptual understanding. After 2006, as more remote (and virtual) labs were used and reported on, Brinson (2015) was able to review 56 empirical studies comparing non-traditional labs (remote and virtual) to traditional labs (hands-on). He found that learning outcomes were equal or better from non-traditional than from traditional labs. This review, however, did not make a distinction between the types of non-traditional labs – remote and virtual – and it did not specifically focus on one type of education (e.g., secondary or higher education). This distinction between different types of labs was made in a large scale study on learning outcomes from remote labs, simulated labs, and hands-on labs (Corter, Esche, Chassapis, Ma, & Nickerson, 2011). These authors found that students learn well from any type of lab, and that several social and motivational factors highly influence learning outcomes. For example, time on task appeared to be relevant as well as whether data for their tasks was collected individually or collectively. Regarding the educational value of remote labs, remote labs appeared to be just as effective as hands-on labs for student learning, even though students rated the effectivity of the remote labs lower.

4.3 Present study

The abovementioned review studies did not explicitly focus on higher education. Moreover, findings on effects of remote labs are difficult to disentangle from effects of simulated labs in the context of

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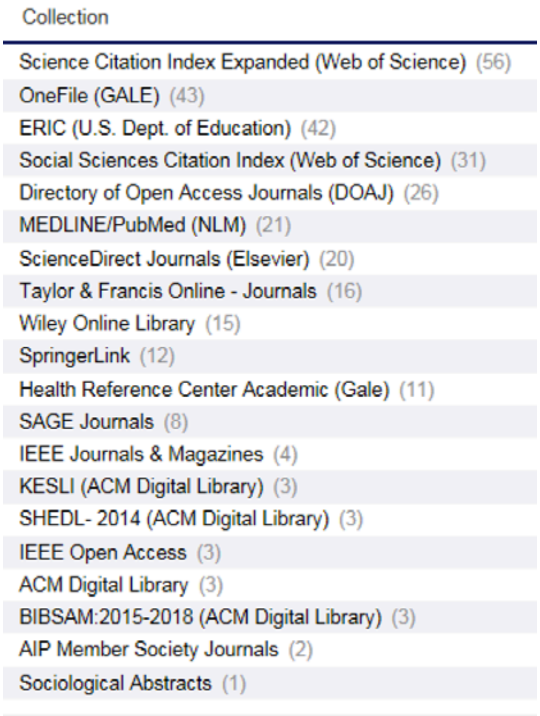
higher education, because these different types of non-traditional labs are often examined together as one type of lab. In addition, only a few studies have been carried out on the effectivity of remote labs. This effectivity measure is often limited to a knowledge test on (theoretical) content and a student experience survey (see Brinson, 2015; Ma & Nickerson, 2006) while the learning goals of remote labs often conveyed much more. For example, remote labs are also used to engage students in real, professional, practice (as opposed to only theory), and to stimulate students to collaborate and to learn how to report on lab work. In short, (remote) labs have many more pedagogical goals than is evaluated in both empirical and review studies so far. It is important that we evaluate the effectiveness of remote labs in higher education as thoroughly as possible to get a full picture of the educational benefits of remote labs in higher education. The aim of this current review is therefore to investigate the learning benefits of remote labs in higher education. Therefore we investigate three research questions: (1) What kinds of effects regarding (both cognitive and affective) learning outcomes are examined in the literature?, (2) How are these effects examined (i.e., research design)?, and (3) What results have these studies found?

4.4 Method

4.4.1 Search

A database search was performed on all databases available at the library of University of Leiden. The search terms included variants of the terms remote and online labs and variants of the term higher education. The search was limited to 1) articles, 2) written in English, 3) the past 15 years (i.e., 2003 to 2017), and 4) peer-reviewed results. This resulted in 128 unique articles from 20 databases (see Figure 4.1).



Collection	
Science Citation Index Expanded (Web of Science)	(56)
OneFile (GALE)	(43)
ERIC (U.S. Dept. of Education)	(42)
Social Sciences Citation Index (Web of Science)	(31)
Directory of Open Access Journals (DOAJ)	(26)
MEDLINE/PubMed (NLM)	(21)
ScienceDirect Journals (Elsevier)	(20)
Taylor & Francis Online - Journals	(16)
Wiley Online Library	(15)
SpringerLink	(12)
Health Reference Center Academic (Gale)	(11)
SAGE Journals	(8)
IEEE Journals & Magazines	(4)
KESLI (ACM Digital Library)	(3)
SHEDL- 2014 (ACM Digital Library)	(3)
IEEE Open Access	(3)
ACM Digital Library	(3)
BIBSAM:2015-2018 (ACM Digital Library)	(3)
AIP Member Society Journals	(2)
Sociological Abstracts	(1)

Figure 4.1. List of databases (and number of articles found)

Note. The following search criteria were used. Search in title: remote lab OR remote labs OR remote laboratory OR remote laboratories OR online lab OR online labs OR online laboratory OR online laboratories. Search in entire document: “higher education” OR undergraduate OR graduate OR post-secondary OR tertiary.

4.4.2 Selection

Based on their titles and abstracts articles were included presenting studies on the use of remote labs for education with a focus on student learning (and not on teacher learning or on technical design of an educational lab). Reviews and meta-analyses were excluded, because these do not provide original data from individual studies (e.g., Brinson, 2015). Ninety-four articles were removed and 34 articles remained for further analyses. After reading these 34 articles, another 11 were removed because they appeared not to be about remote labs (e.g., Tota-Maharaj 2012), did not present cognitive or affective outcomes for students (e.g., Farah, Benachenhou, Neveux, & Barataud, 2012), or described the same data as reported in another article included in the review (Machotka, Nedic & Göl, 2008). The final number of articles for the review was 23. All reasons for exclusion are listed in Table 4.1. The manual selection just described was performed by the first author of this paper. Thirteen (10%) of the original 128 articles from database were also read by a second rater (co-author) and there was a 100% match in selection and rejection of articles by both raters.

Table 4.1. Numbers of excluded articles arranged by reasons for exclusion

Reason for exclusion	Number of articles excluded based on information in…	
	Title/abstract	Full article
No remote lab	60	1
review/overview	16	
technical/design	12	7
No educational context	3	
Focus not on higher education students	3	
No evaluation of remote lab		2
Other*		1

*This article described the same data as reported in another article included in the review.

4.4.3 Data-analysis

Details of the 23 selected articles were included in a matrix. This matrix contained information on the remote lab that was described (i.e., discipline, whether students worked in groups), on the research design (i.e., sample size, conditions, number of measurements), and on the cognitive, behavioral, and affective outcome measures (i.e., which measures and instruments were used). This matrix was used to analyze the articles systematically to answer the research question. The information from the matrix is presented in the tables in the results section.

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Table 4.2. Details of articles included in the review

Authors (year)	Discipline	Group work	Research design			
			Group design	**Comparison conditions**	**Measurements**	**N**
1. Azad (2007)	Engineering	No**	Two groups	Remote vs hands-on	Pre-post	"Small number"
2. Barrios et al. (2013)	Engineering	Yes	One group	Remote only	Post only	43
3. Boix et al. (2008)	Engineering	No	One group	Remote only	Post only	22
4. Broisin et al. (2017)	Computer science	Yes	One group	Remote only	Post only	139
5. Chen & Gao (2012)	Engineering	No	Two groups	Remote vs hands-on	Post only	50 (25 remote)
6. Corter et al. (2007)	Engineering	Yes	Two groups***	Remote and simulated vs hands-on	Post only	306 (156 remote)
7. Dominguez et al. (2014)	Engineering	No	One group	Remote only	Post only	71
8. Duro et al. (2008)	Engineering	No	One group	Remote only	Post only	Unknown
9. Fiore & Ratti (2007)	Life science	No	One group	Remote only	Post only	27
10. Geaney & O'Mahony (2016)	Engineering	No	One group	Remote only	Pre-post	40
11. Jara et al. (2011)	Engineering	No	Three cohorts****	Remote vs hands-on	Post only	75 (50 remote)
12. Lang et al. (2007)	Engineering	No	Two groups	Remote vs hands-on	Pre-post	52 (31 remote)
13. Lehlou et al. (2009)	Engineering	Yes	One group	Remote only	Pre-post	48
14. Luthon & Larroque (2015)	Engineering	No	Two groups	Remote vs hands-on	Pre-post	107
15. Malaric et al. (2008)	Engineering	Yes	One group	Remote vs hands-on; within subjects	Post only	70
16. Morgan et al. (2012)	Engineering	Yes	Two cohorts	Remote vs hands-on	Post only	13
17. Nedic & Machotka (2007)	Engineering	Yes	Two cohorts	Remote vs hands-on	Post only	78
18. Nickerson et al. (2007)	Engineering	No**	One group	Remote vs hands-on	Post only	29
19. Sauter et al. (2013)	Physics	No	Two groups	Remote vs simulation	Pre-post	123
20. Soares et al. (2014)	Engineering	Yes	One group	Remote only	Post only	34
21. Tho & Yeung (2016)	Science teaching education	No	One group	Remote vs hands-on	Post only	64
22. Tirado-Morueta et al. (2018*)	Engineering	No	Two groups	Two types of remote labs	Post only	98
23. Uğur et al. (2010)	Engineering	No	One group	Unknown	Unknown	Unknown

*Available online in 2017 and therefore Included in this review (which is limited to 2003-2017).
** Students worked individually in the remote lab reported here, but the system allowed simultaneous access to the lab, so group work would have been possible.
*** Two groups with within-subjects design. Group 1: remote and hands-on. Group 2: simulated and hands-on.
****Three cohorts: 1x hands-on, 2x remote.

4.5 Results

In Table 4.2, an overview is provided of the articles included in this review. All remote labs were conducted in education in science, technology, engineering, and mathematics (STEM) and the majority was conducted in the field of engineering (19 articles). Many of the engineering remote labs focused on controlling of machines, robots, and other devices (Programmable Logic Controllers; PLC) rather than traditional engineering. For some of the remote labs students worked in small groups (8 articles), whereas in other labs students worked individually (15 articles). The authors of two articles on individual lab work indicate that it was technologically possible to work in groups, but that students worked individually in the specific courses that were evaluated in these articles.

4.5.1 Research designs

In all the reviewed articles, remote labs have been evaluated in some way. This was done with research designs which varied from one group (remote lab) posttest only research designs to multiple group (or cohort) pre- and posttest designs comparing remote labs to hands-on labs. Exceptions are articles that (also) compared remote labs to simulated labs (Corter et al., 2007; Sauter, Uttal, Rapp, Downing, & Jona, 2013) and an article that compared two types of remote labs (more active experimentation versus more restricted following of proposed method; Tirado-Morueta et al., 2018). There was a wide range of sample size in the articles, varying from 13 to 306 participants.

4.5.2 Cognitive and behavioral outcomes

Thirteen articles measured cognitive outcomes (see Table 4.3). Cognitive outcomes are split into conceptual knowledge and technical skills. In all thirteen articles, conceptual knowledge is measured and in two of these (i.e., Chen & Gao, 2012; Fiore & Ratti, 2007) technical skills were assessed as well. Conceptual knowledge concerned knowledge and understanding of the topics that were addressed in the labs. Only one article specified the questions that were posed to the students (Sauter et al., 2013). The technical skills that were measured concerned programming skills and development of a supervision system in one article (Chen & Gao, 2012) and familiarity with technical aspects in the other (Fiore & Ratti, 2007). Cognitive outcomes were in most cases measured with a knowledge test ('test' or 'final exam' in Table 4.3). Only a few of these articles (four) did so using a pre-post design. Overall, cognitive outcomes were found to be equal or better in remote labs than in hands-on labs.

The four articles that found remote labs to be equally effective for improving cognitive outcomes (Azad, 2007; Lang et al., 2007; Luthon & Larroque, 2015; Nickerson et al., 2007) all concerned individual work. This could suggest that group work is more beneficial for learning in remote labs than individual work, because the (four) articles describing labs concerning group work all found positive cognitive outcomes for remote labs. Note, however, that there were about the same number of articles (five articles) describing labs with individual work that found positive effects on cognitive outcomes. This indicates that individual work (not only group work) can foster learning from remote labs.

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Table 4.3. Cognitive and behavioral outcomes

Authors (year)	Cognitive outcomes			Behavioral outcomes	
	Outcome type	Instruments	Findings	Measures	Findings
1. Azad (2007)	CK	Test	Equal to hands-on	Access time and duration	Positive: Less time on lab tasks than control group (efficient learning).
4. Broisin et al. (2017)*	CK	Test	Positive correlation test performance and learners’ engagement	Activity logging	Positive learners’ engagement (involvement in practical activities).
5. Chen & Gao (2012)	CK; TS	Report; presentation; final exam	Positive: better programming skills and grasp of automation sequence concepts	Number of completed experiments	Positive: More basic experiments completed, more students completed expansion experiments.
6. Corter et al. (2007)	CK	Test	Positive; remote and simulated ≥ hands-on		
9. Fiore & Ratti (2007)*	CK; TS	Final exam	Positive: technical and conceptual understanding	Usage data	Positive results.
11. Jara et al. (2011)	CK	Final exam	Positive; better than hands-on	Hours of students' work	Positive: Less time on lab tasks than control group (efficient learning).
12. Lang et al. (2007)	CK	Test	Equal to hands-on		
14. Luthon & Larroque (2015)	CK	Tests; surveys; quizzes	Equal to hands-on		
16. Morgan et al. (2012)	CK	Final exam	Positive; higher mark than previous cohort.	Usage data	Increased student interaction with lab: More configurations per student compared to previous local lab courses.
17. Nedic & Machotka (2007)	CK	Report (marks & process)	Positive: higher mark than previous cohort	Usage data	Spent more time checking calculations.
18. Nickerson et al. (2007)	CK	Test; lab assignment	Equal to hands-on		
19. Sauter et al. (2013)	CK	Test	Positive; better than simulated lab on content learned by doing experiments and better research questions; equal on theoretical questions; lower scores on explanation questions.		
23. Uğur et al. (2010)	CK	*Not reported*	Positive		

N.B. Only articles in which cognitive and/or behavioral outcomes were measured are included. CK = Conceptual knowledge. TS = Technical skills. Empty cell in the behavioral outcomes columns means that this was not measured.
*In this article, no comparison was made to hands-on labs regarding behavioral data.

Another way to examine learning benefits is to view the cognitive outcomes in light of behavioral data. Behavioral data was collected as usage data in the (online) remote lab environment and was logged during remote lab work (e.g., access frequency, time, and duration) in seven articles. In five articles the behavioral data was compared to data from another group (see Table 4.2 “Comparison conditions”). Combining the cognitive and behavioral data showed positive results with respect to remote lab learning. Azad (2007) and Jara et al. (2011) found that students learned more efficient in remote labs. That is, these students achieved equal test scores with less time on lab tasks than students working in a hands-on lab. Four other studies that measured behavioral data found positive results for remote labs in general (Fiore & Ratti, 2007), or more specifically found that students in remote labs completed more experiments (Chen & Gao, 2012), performed more configurations (Morgan et al., 2012), and spent more time checking calculations (Nedic & Machotka, 2007). Broisin et al. (2017) actually related behavioral to cognitive outcomes and found a positive correlation between learner engagement (based on activity logging) and test performance.

4.5.3 Affective outcomes

Table 4.4 displays the information regarding affective outcomes reported in 22 (out of 23) articles. All affective outcomes concerned student evaluations which were all measured as post-test only. Overall, students reported positive experiences with remote labs. Taking a closer look at the affective outcomes, we see that they can be separated in three categories: Satisfaction (how much students liked the remote lab), perception of the remote lab (which aspects students appreciated or not), and experienced learning benefits (whether students felt the remote lab improved learning).

Satisfaction was measured in 11 articles and revealed high satisfaction in all of them. Although students in one study initially had a negative opinion, student satisfaction with the remote lab improved in later years (Luthon & Larroque, 2015). Surprisingly, despite the reported satisfaction with the remote lab in the study performed by Corter et al. (2007), students preferred a hands-on lab. This can be explained by the fact that hands-on labs on the one hand were compared to remote and simulate labs together on the other hand. Given that a simulation does not allow to actually work with equipment, it can be assumed that students preferred a hands-on lab.

Table 4.4. Affective outcomes

Authors (year)	Type of outcome	Instruments	Findings
1. Azad (2007)	SAT; PERC; LB	Weekly survey	Positive: Liked, useful, accessible anywhere anytime; same learning experience as hands-on; but major responsibility.
2. Barrios et al. (2013)	PERC	Survey	Positive: Acceptance, usability and usefulness.
3. Boix et al. (2008)	PERC; LB	Survey	Positive: Challenging and interesting; learned more than expected.
5. Chen & Gao (2012)	SAT*; PERC*; LB*	Survey	Positive; equal to or higher than hands-on: challenging, interesting, learned something, will apply in future, course rating, enough exercises, acquired basic concepts, easy to work from home.
6. Corter et al. (2007)	SAT; PERC	Survey	Positive: Remote and simulated labs convenient and reliable; but preference for hands-on.
7. Dominguez et al. (2014)	SAT; PERC; LB	Survey	Positive: Satisfied with structure of lab, motivated, indicate learning has improved.

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8. Duro et al. (2008)	SAT	Survey	Positive: Convenient to do lab assignment remotely.
9. Fiore & Ratti (2007)	SAT**; PERC	Conversation	Positive attitudes and satisfaction compared to other courses of same year.
10. Geaney & O'Mahony (2016)	PERC	Survey	Positive: Availability.
11. Jara et al. (2011)	PERC**	Survey	Positive: Increased curiosity and motivation compared to hands-on.
12. Lang et al. (2007)	PERC	Survey	Positive: Usability (average scores for acceptance and usefulness).
13. Lehlou et al. (2009)	PERC; LB	Survey	Positive: Attitudes; helpful for learning.
14. Luthon & Larroque (2015)	SAT	Survey	First negative, later positive: Lower satisfaction in first year, but increased in later years as remote lab was improved. Especially positive about collaborative learning and autonomous activity.
15. Malaric et al. (2008)	LB*	Survey	Positive: More effective and provided more opportunities to gain knowledge and experience than hands-on lab.
16. Morgan et al. (2012)	LB	Survey	Positive: Contributed to overall achievement level and understanding operation of digital components.
17. Nedic & Machotka (2007)	PERC	Report	Negative: Preference for hands-on (but expectations might have been unrealistic and high).
18. Nickerson et al. (2007)	PERC; LB	Survey	Positive: Convenient in access and scheduling, ease of use; as effective as hands-on.
19. Sauter et al. (2013)	SAT*; PERC*; LB*	Interview	Positive: Preference for remote over simulated lab.
20. Soares et al. (2014)	PERC; LB	Survey	Positive: the 'kits' (remote labs) helped learning and motivated.
21. Tho & Yeung (2016)	SAT; PERC; LB	Survey; interview	Positive: Anywhere anytime accessibility; innovative experiments; improved confidence level of teaching; useful for learning and teaching.
22. Tirado-Morueta et al. (2018*)	SAT; PERC	Survey	Positive: Usefulness and usability.
23. Uğur et al. (2010)	SAT; PERC	*Not reported*	Positive: relaxed and comfortable environment.

N.B. Only articles in which affective outcomes were measured are included. SAT = Satisfaction. PERC = Perception of remote lab. LB = experienced learning benefits.
*A comparison was made; same comparison group as with the cognitive outcome measures.
**A comparison was made; different comparison group as other outcome measures.

Results on perception of the remote labs show that students highly appreciate the accessibility, usability, and convenience of working with remote labs. Students liked being able to work "in" the lab wherever and whenever they wanted. Drawbacks mentioned most often by students were the lack of face-to-face contact with peers and teachers and the responsibility to work autonomously that came with the freedom of the remote lab. The authors of the only article that reported that students had a negative perception of remote labs, indicate that students' expectations of the remote lab might have been high and unrealistic, as some students thought the remote lab computer could carry out commands that the actual equipment could not (Nedic & Machotka, 2007).

Regarding experienced learning benefits, positive learning benefits are reported in all 11 articles that measured this. In two cases students indicated that, although they felt the remote lab improved learning, they also thought it was equally effective for learning as a hands-on lab (Azad, 2007; Nickerson et al, 2007).

4.6 Discussion

In this review of 23 articles on remote labs in higher education, we aimed to examine the learning benefits of remote labs. In order to investigate this, we examined (1) what kinds of effects regarding (both cognitive and affective) learning outcomes were examined in the literature, (2) how these effects were examined, and (3) what results these studies have found.

First of all, we noticed during selection of articles, that there were not many articles examining educational effects of remote labs in higher education. Instead, most of the articles on remote labs which were not included in the review, merely described and evaluated technical aspects of remote labs (see Table 4.1; e.g., Farah et al., 2012). However, it is also important to examine if learning is not impaired by using remote labs instead of hands-on labs (as was the aim of this review). Moreover, there could even be potential benefits of remote labs over hands-on labs, such as more lab-time for students because labs can be run simultaneously. This provides more learning time and may result in better learning. That being said, we now turn to the educational benefits that *were* examined in the reviewed articles. These effects can be split into cognitive, behavioral and affective outcomes. All three types of outcomes potentially tell us something about learning benefits. That is, regarding cognitive outcomes, remote labs could reveal higher grades than hands-on labs. Also, by combining cognitive and behavioral outcomes, efficiency learning could be established. Affective outcomes could reveal positive learning experiences from remote labs, because remote labs provide for example the opportunity to work and learn in a convenient and relaxed learning environment and possibly trigger students' motivation.

Next, we looked at how the cognitive, behavioral and affective outcomes were examined in the reviewed articles. Most articles made a comparison between remote and hands-on labs in a pre-post or post only design, but nine articles only evaluated the remote lab in isolation (post measurement only design). In these evaluations, cognitive outcomes were mainly measured with tests (exams). Behavioral outcomes were measured through collecting usage data in the remote lab environment. All affective outcomes concerned student evaluations which were all measured with posttests only.

Considering the effects that were examined in the articles, we found that overall remote labs were equally or more effective for learning than hands-on labs. This was found for (1) the cognitive outcomes in terms of higher grades, (2) the behavioral outcomes in terms of more interaction with the lab and more efficient learning, and (3) the affective outcomes in terms of satisfaction, perception of the remote labs characteristics, and experienced learning benefits. These positive findings are very promising, but more systematic research to learning benefits of remote labs should be done to draw more robust conclusions (see also limitations and suggestions for future research in the next section). The finding that remote labs are equally or more effective than hands-on labs is in line with the findings from Brinson (2015) who compared non-traditional labs (such as remote labs) to traditional (hand-on) labs.

4.7 Limitations and future research

The main limitation of the articles included in this review is that evaluation of learning benefits was superficial, mainly because this was not the focus of most of the articles. As far as educational benefits were examined, many research designs concerned a post only measurement and lacked an adequate comparison group. In line with these limitations, the current review revealed that learning benefits of remote labs are not systematically and empirically examined in the reviewed literature. Also, in many cases the exact content of tests and surveys was not clear and statistical tests were only done sporadically, often resulting in merely superficial evaluations. The conclusions that are drawn in the previous section are based on the research that was performed in the reviewed articles which contain the limitations just mentioned. This makes it difficult to have a final conclusion of what the educational benefits of remote labs are. In the future more systematic empirical research should be done, focusing on the educational value of remote labs. This does not only concern the research design (i.e., remote lab versus hands-on lab, pre and post course measurements), but also the instruments that are used (standardized, validated) and the method of analysis of the data.

As for the type of labs that were evaluated, two of the nine articles that found positive cognitive outcomes for remote lab learning did so in comparison to simulated labs (Corter et al., 2007; Sauter et al., 2013). Whereas Sauter et al. found positive effects for remote labs compared to simulated labs, Corter et al. found positive results for both remote and simulated labs compared to hands-on labs. Given that these are only two studies, it cannot be said with cer tainty that remote labs are better for cognitive outcomes than simulated labs. Although this was not the focus of the current article, it would be good if future research tries to shed more light on the differential impact of remote, simulated, and hands-on labs on cognitive outcomes.

Most of the reviewed articles concerned remote labs in engineering. Although this is hardly surprising, given that (hands-on) labs are essential to learning in this discipline, it does not mean that remote labs could not have educational benefits in other disciplines, like for example IT. The main asset of remote labs in the reviewed articles was to be able to control (lab) equipment from a distance, but there are also other characteristics of remote labs that could be just as relevant in other settings, such as to be able to cooperate with each other remotely. For example, in courses on development of Internet of Things related products, everything is developed digital and often online. In such a situation which does not concern actual physical lab equipment, it is easy for students to work on their own computer in a digital online environment. Collaboration between students and providing of feedback to students are also easily done online in such a situation, that is, remotely. In this sense, remote labs can be considered as digital lab environments in which the students and their teachers communicate, collaborate, and cooperate remotely. Future research could investigate educational benefits of remote labs in these types of disciplines. Given that remote labs with more focus on collaboration are somewhat different than remote labs with a focus of remotely controlling equipment – like in engineering – the examination of learning benefits should change accordingly, focusing not only on content knowledge and technical skills, but also on several other competences such as collaboration and communication. This idea fits well with the suggestion made by Zervas, Sergis, Sampson, and Fyskilis (2015) for teacher to use the UNESCO ICT competency framework when selecting appropriate remote and virtual labs for their education.

4.8 Conclusion

The main conclusion that can be drawn from this review is that evaluation of educational benefits of remote labs in higher education is only superficial in the articles published so far. Although cognitive, behavioral, and affective results that are found are promising, more research should be conducted to obtain a full picture of all learning benefits of remote labs in different disciplines within higher education.

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