SUPPLEMENTARY MATERIAL

for paper: Evaluating the Use of Virtual Twins in a Control Systems Course

(S. Prohaska, L. Kennes)

Supplementary Material 1: Search Strategy

TABLE 1: SEARCH STRATEGY

Database	Search	Filters applied	Results
IEEE	(("remote lab*" OR "virtual lab*" OR "online lab*" OR "distance learning") AND (in-person OR hands-on OR on-campus OR evaluation)) AND education	2010 - 2022	876
Web Of Science	(("remote lab*" OR "virtual lab*" OR "online lab*" OR "distance learning") AND (in-person OR hands-on OR on-campus OR evaluation)) AND education	2010 - 2022	1.126
Reference lists			31

Supplementary Material 2: List of excluded full-text articles with reason for exclusion

TABLE 2: LIST OF EXCLUDED FULL-TEXT ARTICLES WITH REASONS FOR EXCLUSION

	Reference	Reason for exclusion
1	M. Abdulwahed, Z. K. Nagy, and A. R. Crawford, “Development and evaluation of open educational resources for enhancing engineering students’ learning experience,” in Proceedings of IEEE International Conference on Teaching, Assessment, and Learning for Engineering (TALE) 2012, Aug. 2012, pp. H4C-14-H4C-18. doi: 10.1109/TALE.2012.6360363.	Control group
2	S. AbuShanab, M. Winzker, and R. Brück, “Teaching low-power design with an FPGA-based hands-on and remote lab,” in 2015 IEEE Global Engineering Education Conference (EDUCON), Mar. 2015, pp. 132–140. doi: 10.1109/EDUCON.2015.7095962.	Control group
3	S. AbuShanab, M. Winzker, R. Brück, and A. Schwandt, “A study of integrating remote laboratory and on-site laboratory for low-power education,” in 2018 IEEE Global Engineering Education Conference (EDUCON), Apr. 2018, pp. 405–414. doi: 10.1109/EDUCON.2018.8363259.	Control group
4	S. Alsaleh, A. Tepljakov, A. Köse, J. Belikov, and E. Petlenkov, “ReImagine Lab: Bridging the Gap Between Hands-On, Virtual and Remote Control Engineering Laboratories Using Digital Twins and Extended Reality,” IEEE Access, vol. 10, pp. 89924–89943, 2022, doi: 10.1109/ACCESS.2022.3199371.	Control group
5	E.-S. Aziz, J. E. Corter, Y. Chang, S. K. Esche, and C. Chassapis, “Evaluation of the learning effectiveness of game-based and hands-on gear train laboratories,” in 2012 Frontiers in Education Conference Proceedings, Seattle, WA, USA, Oct. 2012, pp. 1–6. doi: 10.1109/FIE.2012.6462269.	No full-text available
6	A. Barrios et al., “Academic Evaluation Protocol for Monitoring Modalities of Use at an Automatic Control Laboratory: Local vs. Remote,” INTERNATIONAL JOURNAL OF ENGINEERING EDUCATION, vol. 29, no. 6. TEMPUS PUBLICATIONS, IJEE , ROSSMORE,, DURRUS, BANTRY, COUNTY CORK 00000, IRELAND, pp. 1551–1563, 2013.	Results
7	M. A. Bochicchio, A. Longo, L. Vaira, and M. Zappatore, “Fostering online scientific experimentations in universities and high schools: The EDOC project,” in 2015 3rd Experiment International Conference (exp.at’15), Jun. 2015, pp. 337–342. doi: 10.1109/EXPAT.2015.7463291.	Control group
8	D.-A. Buentello-Montoya, L.-E. Garcia-Amezquita, and L.-M. Rico-Gutierrez, “Experiential learning at home in an engineering thermodynamics course,” in 2022 IEEE Global Engineering Education Conference (EDUCON), Mar. 2022, pp. 1275–1278. doi: 10.1109/EDUCON52537.2022.9766608.	Control group
9	C. Bunse, L. Kennes, and J.-C. Kuhr, “On Using Distance Labs for Engineering Education,” in 2022 IEEE/ACM 4th International Workshop on Software Engineering Education for the Next Generation (SEENG), May 2022, pp. 5–11. doi: 10.1145/3528231.3528355.	Control group
10	A. C. Caminero, S. Ros, R. Hernandez, A. Robles-Gomez, L. Tobarra, and P. J. Tolbanos Granjo, “VirTUal remoTe labORatories Management System (TUTORES): Using Cloud Computing to Acquire University Practical Skills,” IEEE Transactions on Learning Technologies, vol. 9, no. 2. IEEE COMPUTER SOC, 10662 LOS VAQUEROS CIRCLE, PO BOX 3014, LOS ALAMITOS, CA 90720-1314 USA, pp. 133–145, Apr. 2016. doi: 10.1109/TLT.2015.2470683.	Intervention
11	Y. Chang, E.-S. Aziz, Z. Zhang, M. Zhang, and S. K. Esche, “Evaluation of a video game adaptation for mechanical engineering educational laboratories,” in 2016 IEEE Frontiers in Education Conference (FIE), Oct. 2016, pp. 1–6. doi: 10.1109/FIE.2016.7757670.	Control group

12	E. J. Davis, K. L. Breno, D. D. Ojennus, T. A. Russell, K. E. Stevens, and K. Wheeler, “Implementation of a Socially Distanced In-Person Laboratory Experience Across the Chemistry Curriculum during the COVID-19 Pandemic at a Small, Liberal Arts University,” JOURNAL OF CHEMICAL EDUCATION, vol. 98, no. 12. AMER CHEMICAL SOC, 1155 16TH ST, NW, WASHINGTON, DC 20036 USA, pp. 4078–4087, Dec. 14, 2021. doi: 10.1021/acs.jchemed.1c00080.	Control group
13	R. De Jesús Navas-González, Ó. Oballe-Peinado, J. Castellanos-Ramos, D. Rosas-Cervantes, and J. A. Sánchez-Durán, “Digital Electronics Practice Projects for an FPGA-based Remote Laboratory,” in 2022 Congreso de Tecnología, Aprendizaje y Enseñanza de la Electrónica (XV Technologies Applied to Electronics Teaching Conference), Jun. 2022, pp. 1–6. doi: 10.1109/TAEE54169.2022.9840627.	Control group
14	L. E. de Vries and M. May, “Virtual laboratory simulation in the education of laboratory technicians-motivation and study intensity,” BIOCHEMISTRY AND MOLECULAR BIOLOGY EDUCATION, vol. 47, no. 3. WILEY, 111 RIVER ST, HOBOKEN 07030-5774, NJ USA, pp. 257–262, Jun. 2019. doi: 10.1002/bmb.21221.	Control group
15	J. Garcia-Zubia et al., “Empirical Analysis of the Use of the VISIR Remote Lab in Teaching Analog Electronics,” IEEE Transactions on Education, vol. 60, no. 2. IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC, 445 HOES LANE, PISCATAWAY, NJ 08855-4141 USA, pp. 149–156, May 2017. doi: 10.1109/TE.2016.2608790.	Control group
16	N. Lima et al., “The VISIR+ project-helping contextualize math in an engineering course,” in 2017 4th Experiment@International Conference (exp.at’17), Jun. 2017, pp. 7–12. doi: 10.1109/EXPAT.2017.7984369.	Control group
17	G. Makransky et al., “Simulation based virtual learning environment in medical genetics counseling: an example of bridging the gap between theory and practice in medical education,” BMC MEDICAL EDUCATION, vol. 16. BIOMED CENTRAL LTD, 236 GRAYS INN RD, FLOOR 6, LONDON WC1X 8HL, ENGLAND, Mar. 25, 2016. doi: 10.1186/s12909-016-0620-6.	Control group
18	D. May, “Cross Reality Spaces in Engineering Education Online Laboratories for Supporting International Student Collaboration in Merging Realities,” INTERNATIONAL JOURNAL OF ONLINE AND BIOMEDICAL ENGINEERING, vol. 16, no. 3. INT ASSOC ONLINE ENGINEERING, KIRCHENGASSE 10-200, WIEN, A-1070, AUSTRIA, pp. 4–26, 2020. doi: 10.3991/ijoe.v16i03.12849.	Control group
19	D. May, B. Morkos, A. Jackson, N. J. Hunsu, A. Ingalls, and F. Beyette, “Rapid transition of traditionally hands-on labs to online instruction in engineering courses,” EUROPEAN JOURNAL OF ENGINEERING EDUCATION. TAYLOR & FRANCIS LTD, 2-4 PARK SQUARE, MILTON PARK, ABINGDON OR14 4RN, OXON, ENGLAND, 2022. doi: 10.1080/03043797.2022.2046707.	No full-text available
20	M. Mitjans et al., “E-LEARNING OF ANATOMY: VIRTUAL PLATFORMS AS A SURROGATE FOR THE IN-PERSON ANATOMY LABORATORY CLASSROOM,” in EDULEARN22 Proceedings, 2022, pp. 5451–5457. doi: 10.21125/edulearn.2022.1289.	Control group
21	S. Odeh, G. R. Alves, M. Anabtawi, M. Jazi, M. Arekat, and I. Gustavsson, “Experiences with deploying VISIR at Al-Quds University in Jerusalem,” in 2014 IEEE Global Engineering Education Conference (EDUCON), Apr. 2014, pp. 273–279. doi: 10.1109/EDUCON.2014.6826102.	Control group
22	P. Phattanawasin et al., “Students’ Perspectives and Achievements toward Online Teaching of Medicinal Chemistry Courses at Pharmacy School in Thailand During the COVID-19 Pandemic,” JOURNAL OF CHEMICAL EDUCATION, vol. 98, no. 10. AMER CHEMICAL SOC, 1155 16TH ST, NW, WASHINGTON, DC 20036 USA, pp. 3371–3378, Oct. 12, 2021. doi: 10.1021/acs.jchemed.1c00606.	Intervention
23	Z. B. Pinter et al., “Effectivity of Distance Learning in the Training of Basic Surgical Skills-A Randomized Controlled Trial,” SUSTAINABILITY, vol. 14, no. 8. MDPI, ST ALBAN-ANLAGE 66, CH-4052 BASEL, SWITZERLAND, Apr. 2022. doi: 10.3390/su14084727.	Control group
24	I. Rahman and M. Johari, “Students’ understanding and skills on voltage and current measurements using hands-on laboratory and simulation software,” EDUCATION AND INFORMATION TECHNOLOGIES, vol. 27, no. 5. SPRINGER, ONE NEW YORK PLAZA, SUITE 4600, NEW YORK, NY, UNITED STATES, pp. 6393–6406, Jun. 2022. doi: 10.1007/s10639-022-10890-3.	Control group
25	D. A. H. Samuelsen and O. H. Graven, “Adopting an exercise program for electronics engineering education utilising remote laboratories for the age of MOOC,” in 2016 IEEE Frontiers in Education Conference (FIE), Oct. 2016, pp. 1–7. doi: 10.1109/FIE.2016.7757578.	Control group
26	I. Syamsuddin, “VILARITY - Virtual Laboratory for Information Security Practices,” TEM JOURNAL-TECHNOLOGY EDUCATION MANAGEMENT INFORMATICS, vol. 8, no. 3. ASSOC INFORMATION COMMUNICATION TECHNOLOGY EDUCATION & SCIENCE, HILMA ROZAJCA 15, NOVI PAZAR, 36300, SERBIA, pp. 1011–1016, Aug. 2019. doi: 10.18421/TEM83-45.	Control group
27	A. L. Tauber, S. M. Levonis, and S. S. Schweiker, “Gamified Virtual Laboratory Experience for In-Person and Distance Students,” JOURNAL OF CHEMICAL EDUCATION, vol. 99, no. 3.	Control group

	AMER CHEMICAL SOC, 1155 16TH ST, NW, WASHINGTON, DC 20036 USA, pp. 1183–1189, Mar. 08, 2022. doi: 10.1021/acs.jchemed.1c00642.	
28	C. Viegas et al., “Impact of a remote lab on teaching practices and student learning,” COMPUTERS & EDUCATION, vol. 126. PERGAMON-ELSEVIER SCIENCE LTD, THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, ENGLAND, pp. 201–216, Nov. 2018. doi: 10.1016/j.compedu.2018.07.012.	Control group
29	D. Weisman, “Incorporating a Collaborative Web-Based Virtual Laboratory in an Undergraduate Bioinformatics Course,” BIOCHEMISTRY AND MOLECULAR BIOLOGY EDUCATION, vol. 38, no. 1. JOHN WILEY & SONS INC, 111 RIVER ST, HOBOKEN, NJ 07030 USA, pp. 4–9, Feb. 2010. doi: 10.1002/bmb.20368.	Control group

Supplementary Material 3: PRISMA flowchart

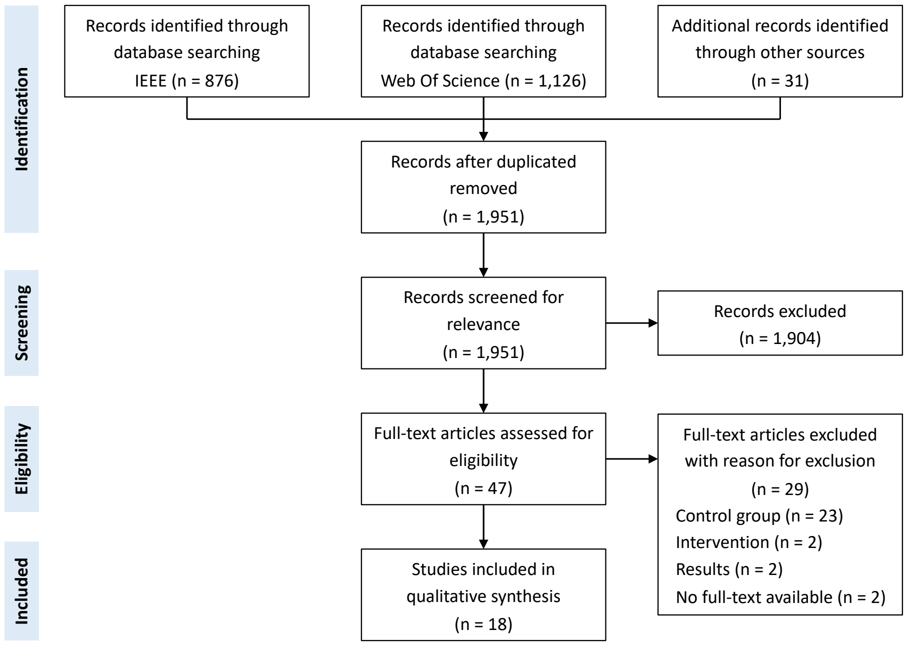

Fig. 1. PRISMA flowchart

Supplementary Material 4: List of included articles

[1] J. E. Corter, S. K. Esche, C. Chassapis, J. Ma, and J. V. Nickerson, “Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories,” COMPUTERS & EDUCATION, vol. 57, no. 3. PERGAMON-ELSEVIER SCIENCE LTD, THE BOULEVARD, LANGFORD LANE, KIDLINGTON, OXFORD OX5 1GB, ENGLAND, pp. 2054–2067, Nov. 2011. doi: 10.1016/j.compedu.2011.04.009.

[2] M. Darrah, R. Humbert, J. Finstein, M. Simon, and J. Hopkins, “Are Virtual Labs as Effective as Hands-on Labs for Undergraduate Physics? A Comparative Study at Two Major Universities,” JOURNAL OF SCIENCE EDUCATION AND TECHNOLOGY, vol. 23, no. 6. SPRINGER, 233 SPRING ST, NEW YORK, NY 10013 USA, pp. 803–814, Dec. 2014. doi: 10.1007/s10956-014-9513-9.

[3] C. L. Dunnagan, D. A. Dannenberg, M. P. Cuales, A. D. Earnest, R. M. Gurnsey, and M. T. Gallardo-Williams, “Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy,” JOURNAL OF CHEMICAL EDUCATION, vol. 97, no. 1. AMER CHEMICAL SOC, 1155 16TH ST, NW, WASHINGTON, DC 20036 USA, pp. 258–262, Jan. 2020. doi: 10.1021/acs.jchemed.9b00705.

[4] K. M. Enneking, G. R. Breitenstein, A. F. Coleman, J. H. Reeves, Y. Wang, and N. P. Grove, “The Evaluation of a Hybrid, General Chemistry Laboratory Curriculum: Impact on Students’ Cognitive, Affective, and Psychomotor Learning,” JOURNAL OF CHEMICAL EDUCATION, vol. 96, no. 6. AMER CHEMICAL SOC, 1155 16TH ST, NW, WASHINGTON, DC 20036 USA, pp. 1058–1067, Jun. 2019. doi: 10.1021/acs.jchemed.8b00637.

[5] A. Farooq and K. Cook-Chennault, “Virtualizing Hands-On Mechanical Engineering Laboratories-A Paradox or Oxymoron,” in 2022 ASEE Annual Conference & Exposition, 2022.

[6] G. Hamed and A. Aljanazrah, “THE EFFECTIVENESS OF USING VIRTUAL EXPERIMENTS ON STUDENTS’ LEARNING IN THE GENERAL PHYSICS LAB,” JOURNAL OF INFORMATION TECHNOLOGY EDUCATION-RESEARCH, vol. 19. INFORMING SCIENCE INST, 131 BROOKHILL CT, SANTA ROSA, CA 95409 USA, pp. 977–996, 2020. doi: 10.28945/4668.

[7] I. Hawkins and A. J. Phelps, “Virtual laboratory vs. traditional laboratory: which is more effective for teaching electrochemistry?,” CHEMISTRY EDUCATION RESEARCH AND PRACTICE, vol. 14, no. 4. ROYAL SOC CHEMISTRY, THOMAS GRAHAM HOUSE, SCIENCE PARK, MILTON RD, CAMBRIDGE CB4 0WF, CAMBS, ENGLAND, pp. 516–523, 2013. doi: 10.1039/c3rp00070b.

[8] R. M. Joji et al., “Perception of online and face to face microbiology laboratory sessions among medical students and faculty at Arabian Gulf University: a mixed method study,” BMC MEDICAL EDUCATION, vol. 22, no. 1. BMC, CAMPUS, 4 CRINAN ST, LONDON N1 9XW, ENGLAND, May 30, 2022. doi: 10.1186/s12909-022-03346-2.

[9] G. Makransky, R. E. Mayer, N. Veitch, M. Hood, B. Christensen, and H. Gadegaard, “Equivalence of using a desktop virtual reality science simulation at home and in class,” PLOS ONE, vol. 14, no. 4. PUBLIC LIBRARY SCIENCE, 1160 BATTERY STREET, STE 100, SAN FRANCISCO, CA 94111 USA, Apr. 11, 2019. doi: 10.1371/journal.pone.0214944.

[10] H. Mostefaoui, A. Benachenhou, and A. A. Benattia, “Design of a Low Cost Remote Electronic Laboratory Suitable for Low Bandwidth Connection,” COMPUTER APPLICATIONS IN ENGINEERING EDUCATION, vol. 25, no. 3. WILEY, 111 RIVER ST, HOBOKEN 07030-5774, NJ USA, pp. 480–488, May 2017. doi: 10.1002/cae.21815.

[11] S. Odeh, G. R. Alves, M. Anabtawi, M. Jazi, M. Arekat, and I. Gustavsson, “Experiences with deploying VISIR at Al-Quds University in Jerusalem,” in 2014 IEEE Global Engineering Education Conference (EDUCON), Apr. 2014, pp. 273–279. doi: 10.1109/EDUCON.2014.6826102.

[12] D. J. Rosen and A. M. Kelly, “Epistemology, socialization, help seeking, and gender-based views in in-person and online, hands-on undergraduate physics laboratories,” PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH, vol. 16, no. 2. AMER PHYSICAL SOC, ONE PHYSICS ELLIPSE, COLLEGE PK, MD 20740-3844 USA, Aug. 28, 2020. doi: 10.1103/PhysRevPhysEducRes.16.020116.

[13] D. J. Rosen and A. M. Kelly, “Working together or alone, near, or far: Social connections and communities of practice in in-person and remote physics laboratories,” PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH, vol. 18, no. 1. AMER PHYSICAL SOC, ONE PHYSICS ELLIPSE, COLLEGE PK, MD 20740-3844 USA, Jan. 12, 2022. doi: 10.1103/PhysRevPhysEducRes.18.010105.

[14] J. J. Serrano-Perez et al., “Traditional vs. Virtual Laboratories in Health Sciences Education,” JOURNAL OF BIOLOGICAL EDUCATION. ROUTLEDGE JOURNALS, TAYLOR & FRANCIS LTD, 2-4 PARK SQUARE, MILTON PARK, ABINGDON OX14 4RN, OXON, ENGLAND, 2021. doi: 10.1080/00219266.2021.1877776.

[15] W.-J. Shyr, “DEVELOPMENT AND EVALUATION OF MECHATRONICS LEARNING SYSTEM IN A WEB-BASED ENVIRONMENT,” TURKISH ONLINE JOURNAL OF EDUCATIONAL TECHNOLOGY, vol. 10, no. 1. TURKISH ONLINE JOURNAL EDUCATIONAL TECH-TOJET, SAKARYA UNIV, ESENTEPE KAMPUSU, SAKARYA, 54187, TURKEY, pp. 89–96, Jan. 2011.

[16] F. Steger, A. Nitsche, A. Arbesmeier, K. D. Brade, H.-G. Schweiger, and I. Belski, “Teaching Battery Basics in Laboratories: Hands-On Versus Simulated Experiments,” IEEE Trans. Educ., vol. 63, no. 3, pp. 198–208, Aug. 2020, doi: 10.1109/TE.2020.2970554.

[17] R. Wang, C. Liu, and T. Ma, “Evaluation of a virtual neurophysiology laboratory as a new pedagogical tool for medical undergraduate students in China,” ADVANCES IN PHYSIOLOGY EDUCATION, vol. 42, no. 4. AMER PHYSIOLOGICAL SOC, 9650 ROCKVILLE PIKE, BETHESDA, MD 20814 USA, pp. 704–710, Dec. 2018. doi: 10.1152/advan.00088.2018.

[18] K. Yiasemides, K. Zachariadou, N. Moshonas, M. Rangoussi, and A. Charitopoulos, “Development and Assessment of a Web-based Platform for an Active Learning Physics Lab Session on the linear regression technique,” in 2022 IEEE Global Engineering Education Conference (EDUCON), Mar. 2022, pp. 946–955. doi: 10.1109/EDUCON52537.2022.9766479.

Supplementary Material 5: Table with results of included studies

Study	Country	Course	Design	Learning Outcomes					Evaluation Instrument							Favoring		
				K/U/P	Prac S	P(S)	P(I)	Comm S	Q	E/T	LR	S/Q	O	I	LP	TL	NTL	Comb
Corter et al. (2011) [1]	USA	E	Parallel-Group Design	X		X		X		X		X				X		
Darrah et al. (2014) [2]	USA	P	Parallel-Group Design	X					X	X							=	
Dunnagen et al. (2020) [3]	USA	C	Feasibility Study	X					X			X					=	
Enneking et al. (2019) [4]	USA	C	NA	X	X	X					X		(X)		X		=	
Farooq et al. (2022) [5]	USA	MAE	Mixed-Method Convergent Research Design Method			X					X	X		X		X		
Hamed et al. (2020) [6]	Palestine	P	Quasi-Experimental Design	X	X	X		X		X			X	X			=	
Hawkins et al. (2013) [7]	USA	C	Pre- and Post-Test Design	X	X					X					X		=	
Joji et al. (2022) [8]	Bahrain	MB	NA			X	X					X						X
Makransky et al. (2019) [9]	Denmark	MB	Parallel-Group Design	X		X				X		X					=	
Mostefaoui et al. (2017) [10]	Algeria	EE	Case Study with Control Group	X	X						X	X					X	
Odeh et al. (2014) [11]	Palestine	ICE	Scenario-Based Usability Engineering			X						X					X	
Rosen et al. (2020) [12]	USA	P	Observational, Quasi-Experimental, Non-Equivalent Group Design			X		X				X					=	
Rosen et al. (2022) [13]	USA	P	Quasi-Experimental, Non-Equivalent Group Design			X		X				X				X		
Serrano-Perez et al. (2021) [14]	Spain	BSS	Pre- and Post-Test Design			X						X				X		
Shyr et al. (2011) [15]	China	MC	Case Study with Control Group	X		X						X	X	X			X	
Steger et al. (2020) [16]	Germany	BB	Cross-Over Design	X						X						X		
Wang et al. (2018) [17]	China	PH	NA	X	X	X			X			X			X			X
Yiasemides et al. (2022) [18]	Greece	P	Comparative Evaluation	X						X	X						X	

E = Engineering; P = Physics; C = Chemistry; MAE = Mechanical and Aerospace Engineering; MB = Microbiology; EE = Electrical Engineering; ICE = Instrumentation and Control Engineering; PH = Physiology; BSS = Basic Science Subjects; MC = Mechatronics; BB = Battery Basics

K/U/P = Knowledge/ Understanding/ Performance
Prac S = Practical Skills
P(S) = Perception (Student)
P(I) = Perception (Instructor)
Comm S = Communication Skills

Q = Quiz
E/T = Exam/ Test
S/Q = Survey/ Questionnaire
O = Observation
I = Intervention
LP = Laboratory Practical

TL = Traditional Lab
NTL = Non-Traditional Lab
Comb = Combination
"=" indicates no different between NTL and TL

Most studies (14 papers) reported only two laboratory groups: traditional laboratory and non-traditional laboratories. Three papers [2, 8, 17] evaluated three different laboratory groups: traditional laboratory, non-traditional laboratory as replacement and non-traditional laboratory as supplement to the traditional one. Only one paper [4] investigated the non-traditional laboratory as supplemental to the traditional laboratory in comparison to a traditional laboratory.

Supplementary Material 6: Table of Learning Outcomes

Type of rater	Question / Outcome	Likert-scale	Refers to hypothesis
Student	Perceived degree of difficulty	7-point	1)
	Time spent with the laboratory content	-	3)
	Comparison between virtual twin and real representation	5-point	2)
	Satisfaction	7-point	2)
Lab engineer	Perceived preparation of students	9-point	1)
	Assistance needed	9-point	1)
Professor	Intermediate Assessment	-	1)

Supplementary Material 7: Intermediate Assessment

1st Intermediate Assessment (max. 32 points)

1) conceptual understanding

2a) conceptual understanding

2b) conceptual understanding

3a) conceptual understanding

3b) knowledge

2nd Intermediate Assessment (max. 23 points)

1a) knowledge

1b) knowledge / conceptual understanding

1c) knowledge / conceptual understanding

2a) calculating

2b) conceptual understanding

2c) conceptual understanding

3d) conceptual understanding

Supplementary Material 8: Formula for *DistLab* effect

$$\textit{DistLab}\text{ effect} = (\mu_{A1} - \mu_{A2}) - (\mu_{B1} - \mu_{B2})$$

μ_{A1} = Expected value for Sequence A in Period 1

μ_{A2} = Expected value for Sequence A in Period 2

μ_{B1} = Expected value for Sequence B in Period 1

μ_{B2} = Expected value for Sequence B in Period 2

Supplementary Material 9: Transformation of 95% confidence intervals

Question / Outcome	Likert-scale	95% CI	Transformed 95% CI [-100;100]
Perceived degree of difficulty	7-point	[-0.6115; 0.7931]	[-10.1919; 13.2175]
Time spent with the laboratory content	-	[1.8523; 5.7451]	[20.5811; 63.8347]
Perceived preparation of students	9-point	[-0.0602; 5.6316]	[-0.7527; 70.3956]
Assistance needed	9-point	[-1.2067; 3.2067]	[-15.0837; 40.0837]
Intermediate Assessment	-	[-7.4189; 10.5389]	[-7.4189, 10.5389]