Quo Vadis, Laboratorium — (Non-)Pervasiveness of Cross-Reality Laboratories in German Educational Research

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Quo Vadis, Laboratorium — (Non-)Pervasiveness of Cross-Reality Laboratories in German Educational Research

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***Abstract*—What is the current state of educational research regarding Cross-Reality Laboratories in Germany? To answer this question a large scale literature survey was conducted on the IEEE Xplore database. The survey yielded 323 papers, 55 (17% of all surveyed papers) of which were investigated in detail after application of inclusion and exclusion criteria. We evaluated for Cross-Reality type, Didactic model, discipline, evaluation results, as well as target education level. We can conclude that research on these Laboratories is a current focus. However, some weaknesses were identified, namely that over half of the papers do not include a didactic concept and research on newer technologies (Take-Home Lab, AR, Ultra-Concurrent Lab) is still lacking.**

***Index Terms*—Cross-Reality Laboratories, Didactic Concepts, Literature Survey, Laboratory Education**

I. Introduction

Laboratories in (higher) education have a long history. Laboratory education dates back to the 19th century [2, p. 202]. Over the centuries Laboratories were used, Laboratories (e.g., see [3]) and Laboratory education (e.g., see [2], [4], [5]) has changed drastically. With the introduction of digital technologies, new types of so-called Cross-Reality Laboratories (see Sec. III-A for a definition) have risen to importance [6, pp. 4-5]. These new kinds of Laboratory bring new advantages (e.g., 24/7 availability, growth potential with increasing student numbers, or safety; see [7]) to education, although some challenges still exist for implementing them (e.g., reduced student-instructor contact time, see [7]; or providing a laboratory experiment with the same degree of freedom as a Physical Laboratory, see [8]).

Since these Cross-Reality Laboratories seem useful and helpful for education, they should be researched. However, digitalisation in higher education in Germany is lagging behind [9], where only a limited number of digital tool are being used and learning management systems being perceived as the most useful tools [10]. In this context, we want to find out how far Cross-Reality Laboratories are researched in Germany. Specifically, we want to answer the following research questions:

RQ1 To which degree are Cross-Reality Laboratories present in German education research?

RQ2 How are Cross-Reality Laboratories researched in German education research?

This research was part of the project *Flexibel kombinierbare Cross-Reality Labore in der Hochschullehre: zukunftsfähige Kompetenzentwicklung für ein Lernen und Arbeiten 4.0* (CrossLab) [1], which is funded by the *Stiftung Innovation in der Hochschullehre*, Germany.

II. Related Work

Literature surveys are an often employed tool to gain insight into the current status of research area, including in education research. For example, Gardner et al. investigated non-formal computer science education in K-12 [11], whereas Pires et al. surveyed aptitude to learn programming [12]. Surveys also investigate methodologies, not only content, as done by Sabri et al. [13]. Renner et al. give a comprehensive overview over the current approaches to literature surveys [14].

A special mention should go to works such as by Torres Gómez et al. [15], who have a similar goal as to investigate general trends in German engineering education. On the other hand, several studies investigate literature that compares remote, simulated, and traditional Laboratories in an educational context, e.g.: [16], [17], [18], [19].

Cooper [20] defines a scheme for categorising different types of literature surveys according to six categories. We can apply this scheme to our study as follows:

- **Focus**: research outcomes; practices or applications
- **Goal**: integration
- **Perspective**: neutral representation
- **Coverage**: exhaustive
- **Organisation**: conceptual
- **Audience**: specialized scholars

III. Relevant Concepts

This sections briefly presents key concepts relevant for this study, namely Cross-Reality Laboratories and didactic models.

A. Cross-Reality Laboratories

As this study investigated the state of Cross-Reality Laboratories in Germany, some structured understanding of the concept of “Cross-Reality Laboratory” is needed. We decided to align ourselves with the different types of Laboratories as outline by May et al. [21, p. 795f]:

- **Take-Home-Laboratories** feature some portable setup that students can take with them to use at their own leisure, usually in combination with their own PC/tablet/mobile device or such.
- **Augmented Reality Laboratories** utilize AR technologies to supplement a Physical Laboratory with additional information, such as displaying telemetry or visualizing normally invisible processes, e.g., fluid currents and turbulences.
- **Remote Laboratories** utilize the internet to grant remote access to Physical Laboratory setups, e.g., by remote-controlling a robot arm.
- **Ultra-concurrent Remote Laboratories** substitute Physical hardware through (multiple) pre-recorded experiments, both video and results, for a given input configuration.
- **Virtual Laboratories** employ VR and simulation software to conduct experiments without relying on any Physical Laboratory equipment.

B. Didactic Models

To categorise the didactic model a Laboratory employs, some form of framework or taxonomy of didactic world views is needed. We decided to apply the works of Terhart [22] as framework, resulting in six different models into which a Laboratory may be sorted. Terhart categorizes three of his six didactic models as a *traditional* school of thought [22, pp. 15-20]:

- **Theory of Education** (*Bildungstheoretische Didaktik*): Teaching-Learning-Activities (TLAs) are defined by being well-planned out and thoroughly structured; content is combined in sensible contexts; and education is understood as a means of to facilitate maturity and cultural understanding of students.
- **Theory of Learning** (*Lerntheoretische Didaktik*): A TLA respects the individual starting point of each learner. In addition, based on empiric educational research, Goals, Contents, Methods and Means of a TLA interact with and influence each other. Instruction serves as goal-oriented organisation of teaching-learning-processes.
- **Communicative Didactics** (*Kommunikative Didaktik*): A communicative TLA is not centred around its content or organisation but rather around the processes and influences of social interaction within the learning context. The focus thus shifts from *instruction* to *interaction* with the goal of establishing communication on eye-level between every actor within the learning space.

The other three types are grouped as *Neuanfänge*, which may best be translated as “restart”, “comeback” or “new beginning”; however, here it is used to mean *innovation* or *new approaches* [22, p. 13; pp. 20-27]:

- **Constructivism** (*Konstruktivistische Didaktik*): Constructivism postulates that all knowledge is not absolute but a construct, and similarly that learning is an act of (communal) construction. Instruction increases the probability of learning but doesn’t directly cause it, and any and all learning outcomes are to be seen as successes. It shares some similar viewpoints with communicative didactics.
- **Learning Path Didactics** (*Bildungsgangdidaktik*): Students are assumed to acquire content knowledge only when they assign individual meaning to it. Thus, while standardized educational paths based on objective societal norms are offered, each learner finds their own individual way through the learning process.
- **Neurodidactics** (*Neurodidaktik*): Based on constructivism, this approach utilizes insights from neuroscience and psychology by taking the learning environment and circumstances of students into consideration to scaffold cognitive development and knowledge gain. The focus is on learning methods rather than teaching methods.

Please note that according to this definition, organisational concepts like *Project-Based Learning* and *Problem-based Learning* [23] alone do not count as a didactic model. Such organisational concepts allow for different didactic models (e.g., see [24, p. 531f]). When implementing such an organisational model, one still needs a theory of learning and therefore a (separate) didactic model.

IV. Method: Conducting the Literature Survey

This section describes how the literature survey was conducted.

A. Query and Platform

To identify the current status of educational research in Germany, we included the conferences listed by the IEEE Education Society[1]. We chose the IEEE Education Society since we believe this scope can give a more representative overview over German research in contrast to an outlet more focusing on Cross-Reality Laboratories (such as the conferences organised by the International Association of Online Engineering). In addition, the two journals *IEEE ToE: Transactions on Education* and *IEEE TLT: Transaction Learning Technologies* of the IEEE Education Society were included[2]. To include recent publications, we searched on IEEE Xplore for all publication with at least one author with German affiliation between 2020 and 2024. For the exact *Command Search* string used, see Fig. 1. The search was conducted on Feb. 18th 2025.

B. Inclusion and Exclusion Criteria

The following criteria were used to determine whether a paper was included in the study.

[1]https://ieee-edusociety.org/conferences/about-conferences, last accessed 2025-04-02. Please note that the *LWMOOCs* changed its name to *DEMOcon*, hence we only included *DEMOcon* in the survey.

[2]Since *IEEE Access* is not primarily focused on education and *IEEE Revista Iberoamericana de Tecnologías del Aprendizaje* focusses on the Ibero-American community, those journals were not included despite listed by the society.

```
(((
   (
      ("Publication Title":EDUCON) OR
      ("Publication Title":"Frontiers in Education") OR
      ("Publication Title":"Transactions on Education") OR
      ("Publication Title":"GeCon") OR
      ("Publication Title":"Transaction on Learning Technologies") OR
      ("Publication Title":"EDUNINE") OR
      ("Publication Title":"TALE") OR
      ("Publication Title":"TALE") OR
      ("Publication Title":"DEMOcon")
   )
   AND ("Affiliation":Germany)
)))
```

Figure 1: *Command Search* string used in IEEE Xplore. Unfortunately, TALE was included twice in the string. This should not impact the results. This was only found after most of the study was done. For reproducibility purpose, we want to present the search query exactly as used. After the search, the years 2020 to 2024 were selected manually in the IEEE Xplore web page.

- **Inclusion 1: German or English Language.** Since all papers are taken from IEEE Xplore, it is expected that all papers fulfil this criterion.
- **Inclusion 2: Paper describes either a Laboratory or something done in a Laboratory.** A Laboratory is defined for the purpose of this study as a place for a practical activity where workers or learners can achieve one or more of the learning outcomes of [25] by performing the activity.
- **Exclusion 1: Not a Cross-Reality Laboratory.** A Cross-Reality Laboratory is either a Laboratory as described in [21] (see Subsec. III-A) or a new type of Laboratory which differs from a traditional, Physical Laboratory.
- **Exclusion 2: No concrete description of a Laboratory.** A Laboratory is described to a reasonable degree if and only if something reasonably similar can be recreated by adhering to the provided description.

C. Analysed Variables

To answer our research question as defined in **RQ2**, the following variables are collected:

V1 Type of Cross-Reality Laboratory (see Subsec. III-A)
V2 Didactic model (see Subsec. III-B)
V3 (Scientific) discipline(s) in which the Laboratory is employed[3]
V4 Evaluation efforts and corresponding results
V5 Educational level (K-12, degree programme, study semester, ...)

Since a Laboratory can combine multiple Cross-Reality types, for V1, a single Laboratory may be labelled with all applicable types. In addition, since Laboratories might contain parts from traditional settings (e.g., by combining simulation and physical assembly), a label for Physical Labs has also been included.

For V2 we also noted that not all Laboratories have their didactic model described. Additional manifestations have arisen during the study, see Sec. VI-A.

V3, too, allows for multi-labelling since like V1, since a Laboratory may be employed in several disciplinary contexts or even interdisciplinarily. Furthermore, as no external framework to define a catalogue of disciplines was used, the value space for V3 was extended inductively over the course of the survey. Again, some Laboratories have no clear description of their target audience.

The purpose of V4 is to identify whether, in general, Cross-Reality Laboratories have a positive effect on learning. As most evaluations presumably differ from each other methodically and thus cannot be directly compared, only the general tendencies of the results are analysed[4]. Since a paper can have multiple variables which can have different results, it might at the same time have positive, inconclusive, and negative results.

Finally, V5 is used to fuel a discussion about the different educational levels Cross-Reality Laboratories are used with and to compare them against each other. We differentiate between different levels in the Bachelor's degree (or undergraduate), Master's degree (or graduate), schools (K-12), vocational training, and for academic staff.

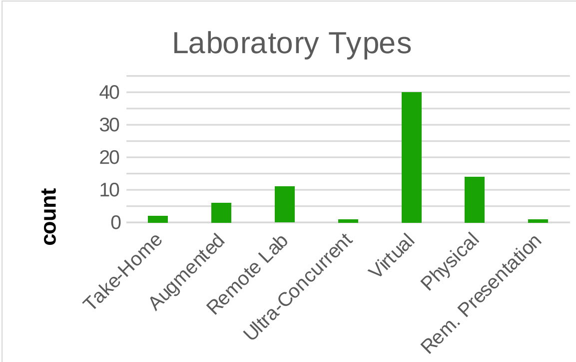
V. Results

For our literature survey, we were able to extract a total of 323 papers from IEEE Xplore. From these, a total of 55 ($\approx$17%) matched our inclusion and exclusion criteria (see Sec. IV-B) which were analysed further.

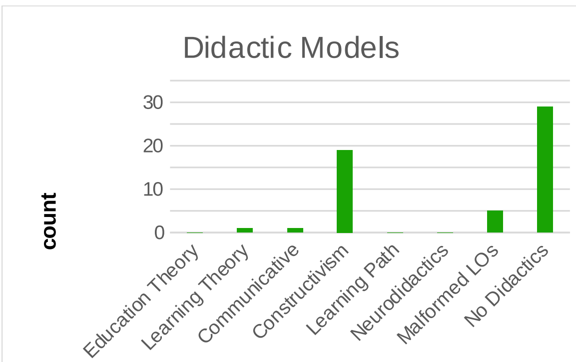
For V1: Most of the included studies were concerned with Virtual Labs (see. Fig. 2a), with Remote Labs following at a second place. Take-Home Labs, AR and Ultra-Concurrent Labs all have under 10 mention. A special note should go to [36] who presented a **Remote Presentation Laboratory** where the experiment is shown and executed by an instructor and interactivity is created by quizzes and similar activities, which is a kind of Cross-Reality Lab which did not fit into

[3]If a paper only defines *STEM* (or similar subject groupings) it is categorized as *unknown discipline* since we cannot clearly identify the addressed target groups.

[4]This also sidesteps issues like [26], [27] when directly comparing results.



(a) Distribution of the different Laboratory Types found by the survey.



(b) Didactic Models addressed by the surveyed studies.

Figure 2: Distribution of Laboratories over the Laboratory Types (III-A) and Didactic Models III-B.

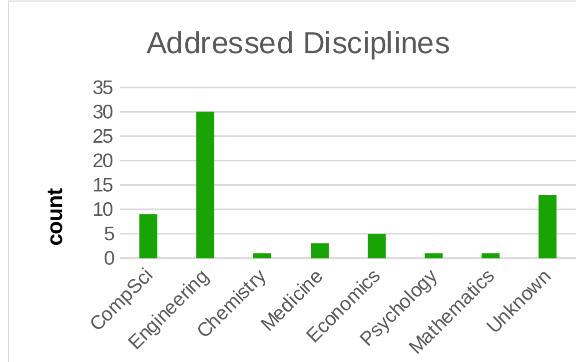
the categories of [21, p. 795f]. **Physical Laboratories** can not occur alone because of IV-B, so we can look at which combinations are most often occurring with Physical Labs. Twelve papers reported Physical Labs combined with Virtual Labs and two reported Physical Labs combined with Remote Labs.

For V2: We can see in Fig. 2b that more than half of the papers do not include a didactic model as defined in Sec. III-B. Of those who have a didactic model, almost all used constructivism.

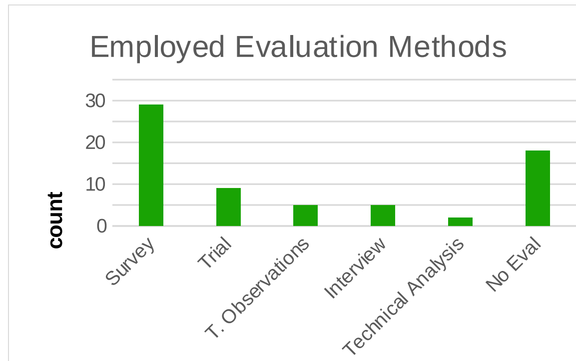
For V3: Fig. 3a shows that almost all Laboratories were either in engineering or computer science. Besides those, we found Cross-Reality Laboratories in chemistry, medicine, economy, psychology, and mathematics.

For V4: Of the studies that reported any form of evaluation, 32 reported positive results, two reported negative results, and six were inconclusive. As evaluation methods go, the most preferred by far was survey, with trial, (teachers') observation, interview, and technical analysis all being used by less than 10 papers.

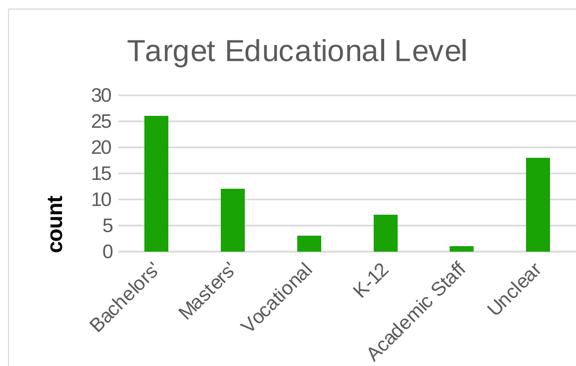
Finally, for V5: Most Laboratories are used in higher education (see Fig. 3c), with vocational training, K-12 and academic staff all being addressed by less than 10 papers.



(a) Disciplines in which the Laboratories are used.



(b) The different types of evaluation presented in the surveyed studies.



(c) The educational levels addressed by the labs.

Figure 3: Distributions of the surveyed studies over V3-V5.

VI. Discussion

Based on the results, we can answer our research questions.

For **RQ1**, we can conclude that Virtual Labs (and possibly Remote Labs) are actually well researched in Germany, while newer technologies such as Take-Home Labs, AR and Ultra-Concurrent Labs still need some more focus. Interestingly, a small part of Laboratories combine both Cross-Reality and Physical Labs. The most common combination we found consisted of Physical and Virtual Labs.

For **RQ2**, we can conclude that most Laboratories still lack a didactic model. This is not optimal since without a didactic concept, it is hard to tell how to design the lab so that students can still learn. Unfortunately, this is in line with literature (see [28] [29, p. 15]) and something we need to improve. For disciplines, we mostly see engineering; however, this might be due to the selection of outlets based on the IEEE Education Society which might have brought a bias into the study. As for target groups, mostly higher education is targeted, although we see some Laboratories in K-12, for vocational training, and for training academic staff.

Besides these general observations, we also want to discuss some more specific points we noticed during the study.

A. Outcome-Based Education

In the study, we noted that some authors used the term *learning outcome* in ways we did not anticipate. For this study, we used for learning outcomes the definition found in [30, Chap. 7] for *intended learning outcome*, where the focus is on *"[...] what the student should be able to perform after teaching that couldn't be performed previously"* [30, p. 118]. We feel that this definition can be seen as generally understood, since similar definitions can be found by different authors, e.g., [31, p. 213]. For another example, Hartel and Foegeding refer to *outcomes* as the lowest of three hierarchical concepts in education, below *objective* and *competency*. They understand an *outcome* as something that describes a specific, measurable ability that students acquire [32, p. 69]. Anderson et al. define a learning outcome[5] as a combination of a *cognitive process* (something students do) that is applied to some form of *knowledge* (some often domain-specific object of interaction and discussion) [33, p.12-14] – a comparable notion to the intended learning outcomes of Biggs and Tang.

Unfortunately, we found a number of papers where the authors used the term *learning outcome* without following this or as similar definition. Almost always, no definition is given. In these cases, it is not clear what exactly they mean when they talk, hence we added a tag to identify such cases.

For a brief overview over problems with written learning outcomes, see [34, 5.2.1.][34, 5.2.2.].

B. Defining Cross-Reality Laboratories in Computer Science

One special mention should go to Computer Science. Since most Laboratories are digital in one way or another, it is hard to differentiate between "Physical" Laboratory and Cross-Reality Laboratory. Imagine a Laboratory where students should deploy some software project into a cloud environment. Is this a **Virtual Laboratory** since simulation of a cloud environment is used or is it a **Physical Laboratory** since those cloud tools (even on the server side) are the same as real environments and this is just a standard procedure used in computing? This question is not easy to answer.

For this study, we only considered a Laboratory in computer science to be a Cross-Reality Laboratory if it has some elements especially designed to be Cross-Reality.

[5] Anderson et al. do not use the term *outcome* at all in this regard, instead discussing *objectives* [33, p. 3 footnote] which can be seen as an equivalent.

C. Defining Cross-Reality Laboratories with CAD Software

Similar to Sec. VI-B, computer-aided design (CAD) software can be considered an edge case. In CAD software, the design of a product is done on a computer instead of on paper (or similar). Does this already constitute a **Virtual Laboratory** since the designed artefacts are simulated in software or is this still a traditional tool used during the normal design process?

For this study, we only considered a Laboratory using CAD software a Cross-Reality Laboratory if it is used in a way extending normal design process. The authors believe this decision also captures the intend behind **Virtual Laboratories** as defined in Sec. III-A.

VII. Conclusion

Based on a large literature survey investigating the state of Cross-Reality Laboratories in German Education research, we can say that with 55 papers ($\approx$ 17%) Cross-Reality Laboratories are a well researched topic. For comparison, we excluded 48 papers solely on being non-Cross Reality, which means that the number of Physical and Cross-Reality Laboratories is comparable. Based on our results, we can give some pointers for future research in that topic.

As a start, we should look more into newer technologies for Cross-Reality Laboratories. Our study revealed a lack of research for Take-Home Labs, AR and Ultra-Concurrent Labs. All of those have different advantages we might want to use for teaching, e.g. the high availability and realistic appearance of Ultra-Concurrent Labs, so we should include them more in research.

In addition, we were able to show that over half of Laboratories do not have a didactic concept. Since knowing how to teach is a big contributor to students learning success, this is an area which definitely needs more improvement. We hope that future research will include their thoughts on didactics more.

Finally, the most observed discipline by far is engineering. Since Cross-Reality Laboratories seem to be such a useful tool, we feel it would be beneficial to include it in more disciplines (and report on it). These Laboratories might be a good fit for disciplines like medicine, biology, chemistry, or physics, but maybe even outside of STEM.

It would also be helpful to do similar studies with larger scope. Since we believe that such a literature survey can yield good insights about strengths and weaknesses of the state of research, it would be prudent to increase the scope of such surveys, both in terms of included countries (e.g., Europe or even global) or in term of perspectives (e.g. include different modes of teaching). Even with our limited scope of Cross-Reality Laboratories in Germany, we hope that our results are helpful, both for German as well as international research and teaching.

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The results of the literature survey – presented as a spreadsheet – can be accessed at https://doi.org/10.5281/zenodo.15574554.

REFERENCES

[1] I. Aubel *et al.*, "Adaptable digital labs - motivation and vision of the crosslab project," in *2022 IEEE German Education Conference (GeCon)*. Berlin, Germany: IEEE, 2022, pp. 1–6.

[2] A. Hofstein and V. N. Lunetta, "The role of the laboratory in science teaching: Neglected aspects of research," *Review of Educational Research*, vol. 52, no. 2, pp. 201–217, 1982. [Online]. Available: https://doi.org/10.3102/00346543052002201

[3] C. M. Jackson, *The Laboratory*. John Wiley & Sons, Ltd, 2016, ch. 21, pp. 296–309. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/9781118620762.ch21

[4] A. Hofstein and V. N. Lunetta, "The laboratory in science education: Foundations for the twenty-first century," *Science Education*, vol. 88, no. 1, pp. 28–54, 2004. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/sce.10106

[5] L. D. Feisel and A. J. Rosa, "The role of the laboratory in undergraduate engineering education," *Journal of Engineering Education*, vol. 94, no. 1, p. 121–130, 2005. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2168-9830.2005.tb00833.x

[6] 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 (iJOE)*, vol. 16, no. 03, p. pp. 4–26, Mar. 2020. [Online]. Available: https://online-journals.org/index.php/i-joe/article/view/12849

[7] E. K. Faulconer and A. B. Gruss, "A review to weigh the pros and cons of online, remote, and distance science laboratory experiences," *International Review of Research in Open and Distributed Learning*, vol. 19, no. 2, 2018.

[8] M. Soll *et al.*, "It's a marathon, not a sprint: Challenges yet to overcome for digital laboratories in education," in *Smart Technologies for a Sustainable Future*, M. E. Auer, R. Langmann, D. May, and K. Roos, Eds. Cham: Springer Nature Switzerland, 2024, pp. 220–231.

[9] H. G. Schuetze, "Digitalization of german higher education and the role of europe," *Journal of Comparative & International Higher Education*, vol. 16, no. 2, May 2024. [Online]. Available: https://www.ojed.org/jcihe/article/view/6066

[10] M. Bond, V. I. Marín, C. Dolch, S. Bedenlier, and O. Zawacki-Richter, "Digital transformation in german higher education: student and teacher perceptions and usage of digital media," *International Journal of Educational Technology in Higher Education*, vol. 15, no. 1, p. 48, Dec 2018. [Online]. Available: https://doi.org/10.1186/s41239-018-0130-1

[11] T. Gardner, H. C. Leonard, J. Waite, and S. Sentance, "What do we know about computing education for k-12 in non-formal settings? a systematic literature review of recent research," in *Proceedings of the 2022 ACM Conference on International Computing Education Research - Volume 1*. Lugano and Virtual Event Switzerland: ACM, Aug. 2022, p. 264–281. [Online]. Available: https://dl.acm.org/doi/10.1145/3501385.3543960

[12] J. Pires, A. Gomes, A. R. Borges, and F. B. Correia, "Predicting higher education student's aptitude to learn to program: A systematic literature review," in *Proceedings of the International Conference on Computer Systems and Technologies 2024*. Ruse Bulgaria: ACM, Jun. 2024, p. 242–248. [Online]. Available: https://dl.acm.org/doi/10.1145/3674912.3674949

[13] Z. Sabri, Y. Fakhri, and A. Moumen, "Serious games in higher education: A literature survey using topic modeling," in *2022 2nd International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)*. Meknes, Morocco: IEEE, Mar. 2022, p. 1–5. [Online]. Available: https://ieeexplore.ieee.org/document/9738213/

[14] A. Renner, J. Müller, and A. Theissler, "State-of-the-art on writing a literature review: An overview of types and components," in *2022 IEEE Global Engineering Education Conference (EDUCON)*. Tunis, Tunisia: IEEE, Mar. 2022, p. 1895–1902. [Online]. Available: https://ieeexplore.ieee.org/document/9766503/

[15] J. T. Gómez, N. Spicher, and J. Haase, "Quo vadis? - comprehensive viewpoint on german educational research in engineering," in *2023 IEEE Global Engineering Education Conference (EDUCON)*. Kuwait, Kuwait: IEEE, May 2023, p. 1–10. [Online]. Available: https://ieeexplore.ieee.org/document/10125228/

[16] R. Heradio, L. de la Torre, D. Galan, F. J. Cabrerizo, E. Herrera-Viedma, and S. Dormido, "Virtual and remote labs in education: A bibliometric analysis," *Computers & Education*, vol. 98, p. 14–38, Jul. 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360131516300677

[17] R. Heradio, L. de la Torre, and S. Dormido, "Virtual and remote labs in control education: A survey," *Annual Reviews in Control*, vol. 42, p. 1–10, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1367578816300281

[18] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Computing Surveys*, vol. 38, no. 3, p. 7, Sep. 2006. [Online]. Available: https://dl.acm.org/doi/10.1145/1132960.1132961

[19] J. R. Brinson, "Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research," *Computers & Education*, vol. 87, p. 218–237, Sep. 2015. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360131515300087

[20] H. M. Cooper, "Organizing knowledge syntheses: A taxonomy of literature reviews," *Knowledge in Society*, vol. 1, no. 1, p. 104, 1988.

[21] D. May, C. Terkowsky, V. Varney, and D. Boehringer, "Between hands-on experiments and cross reality learning environments – contemporary educational approaches in instructional laboratories," *European Journal of Engineering Education*, vol. 48, no. 5, pp. 783–801, 2023. [Online]. Available: https://doi.org/10.1080/03043797.2023.2248819

[22] E. Terhart, "Allgemeine Didaktik: Traditionen, Neuanfänge, Herausforderungen [general didactics: traditions, restarts, challenges]," in *Perspektiven der Didaktik. Zeitschrift für Erziehungswissenschaft*, M. A. Meyer, M. Prenzel, and S. Hellekamps, Eds. Wiesbaden, Germany: VS Verlag für Sozialwissenschaften, 2008, vol. 10, pp. 13–34.

[23] R. A. Ralph, "Post secondary project-based learning in science, technology, engineering and mathematics," *Journal of Technology and Science Education*, vol. 6, no. 1, p. 26–35, Mar 2016. [Online]. Available: https://www.jotse.org/index.php/jotse/article/view/155

[24] W. Hung, "Theory to reality: a few issues in implementing problem-based learning," *Educational Technology Research and Development*, vol. 59, no. 4, pp. 529–552, Aug 2011. [Online]. Available: https://doi.org/10.1007/s11423-011-9198-1

[25] M. Soll *et al.*, "Integration of learning outcomes for stem laboratories into a new learning outcome catalogue," in *2025 IEEE Global Engineering Education Conference (EDUCON)*. London, United Kingdom: IEEE, in press.

[26] E. Terhart, "Has john hattie really found the holy grail of research on teaching? an extended review of visible learning," *Journal of Curriculum Studies*, vol. 43, no. 3, pp. 425–438, 2011. [Online]. Available: https://doi.org/10.1080/00220272.2011.576774

[27] R. Schulmeister and J. Loviscach, "Kritische anmerkungen zur studie „lernen sichtbar machen" (visible learning) von john hattie," *SEMINAR 2/2014; Lehren & Lernen vol. 41 no. 4*, 2014. [Online]. Available: http://rolf.schulmeister.com/pdfs/Seminar2-2014_S121-130.pdf

[28] M. Soll, "What exactly is a laboratory in computer science?" in *2023 IEEE Global Engineering Education Conference (EDUCON)*, 2023, pp. 1–9.

[29] A. E. Tekkaya *et al.*, Eds., *Das Labor in der ingenieurwissenschaftlichen Ausbildung: zukunftsorientierte Ansätze aus dem Projekt IngLab: acatech Studie*, ser. acatech Studie. München: Herbert Utz Verlag GmbH, 2016.

[30] J. Biggs and C. Tang, *Teaching for quality learning at university: what the student does*, 4th ed. Maidenhead, England New York, NY: Society for Research into Higher Education & Open University Press, 2011.

[31] D. R. Krathwohl, "A revision of bloom's taxonomy: An overview," *Theory Into Practice*, vol. 41, no. 4, pp. 212–218, 2002. [Online]. Available: https://doi.org/10.1207/s15430421tip4104_2

[32] R. Hartel and E. Foegeding, "Learning: objectives, competencies, or outcomes?" *Journal of Food Science Education*, vol. 3, no. 4, p. 69–70, oct 2004. [Online]. Available: https://ift.onlinelibrary.wiley.com/doi/10.1111/j.1541-4329.2004.tb00047.x

[33] L. W. Anderson *et al.*, Eds., *A taxonomy for learning, teaching, and assessing: a revision of Bloom's taxonomy of educational objectives*, abridged ed. Longman, 2001.

[34] L. Kobras, "Inwieweit gehen realität und empfehlung auseinander? analyse von pflichtmodulen im vergleich zu den gi-empfehlungen für informatik-bachelorstudiengänge," Master Thesis, University of Hamburg, Hamburg, 2024. [Online]. Available: http://edoc.sub.uni-hamburg.de/informatik/volltexte/2025/300/

Papers Included in Literature Research

[35] T. Fuhrmann, "Teaching digital electronics principles by connecting diverse technologies," in *2024 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE)*, 2024, pp. 1–5.

[36] F. Keil, D. Riehl, and K. Hofmann, "Converting an undergrad-lab to an interactive e-learning experience that enables student teamwork," in *2021 IEEE Frontiers in Education Conference (FIE)*, 2021, pp. 1–5.

[37] D. Riehl, F. Keil, and K. Hofmann, "From breadboard to complex electronic systems - introducing a heterogenous group of undergrad students to design and analysis of electronic circuits," in *2023 IEEE Frontiers in Education Conference (FIE)*, 2023, pp. 1–5.

[38] I. Drămnesc, E. Ábrahám, T. Jebelean, N. Fachantidis, G. Kusper, and S. Stratulat, "A european project on ai-based robotics," in *2024 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE)*, 2024, pp. 1–7.

[39] R. Al Amin, V. Wiese, M. M. Rahman, S. Jacobs, S. Jaschke, and R. Obermaisser, "Architecture of iot-based collaborative laboratory for reconfigurable soc: Review and development," in *2023 IEEE 2nd German Education Conference (GECon)*, 2023, pp. 1–6.

[40] S. Jacobs, T. Hardebusch, N. Gerhard, E. Franke, H. Peters, and S. Jaschke, "Promoting competences for the digital world by an educational escape room," in *2023 IEEE 2nd German Education Conference (GECon)*, 2023, pp. 1–4.

[41] F. Dillenhöfer, B. Künne, and U. Willms, "Neologised teaching concept and materials combine remote teaching and hands-on activities," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–4.

[42] I. Aubel, D. Kaiser, and M. Bertau, "Rectification laboratory - from in-lab to remote - the development story," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–5.

[43] B. Forster-Heinlein, H. Epperlein, and E. Mille, "The passau math museum: Hands-on mathematics by students for schoolkids," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[44] T. Penthong, E. Gümrükcü, and F. Ponci, "Laboratory of power system automation: an example of activity," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[45] L. Karal, B. Rathke, and W. Reichwein, "Vidar lab: A virtual network environment for project-based learning of undergraduate students," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[46] J. T. Gómez and L. Stratmann, "Actively supporting k-12 education from university academy programs," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–5.

[47] J.-C. Kuhr and M. Müller, "Self-determined distance learning by virtual twins in undergraduate control systems labs," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[48] A. Henrich and T. Schultze, "Work in progress: Do students benefit from using vr as a tool in engineering exercises?" in *2022 IEEE World Engineering Education Conference (EDUNINE)*, 2022, pp. 1–4.

[49] J. Nau and K. Henke, "Goldi labs as fully integrated learning environment," in *2024 IEEE World Engineering Education Conference (EDUNINE)*, 2024, pp. 1–6.

[50] M. Striegel, J. Erasmus, and P. Jain, "Evaluating augmented reality for wireless network security education," in *2021 IEEE Frontiers in Education Conference (FIE)*, 2021, pp. 1–9.

[51] B.-M. Block and B. Haus, "New ways in engineering education for a sustainable and smart future," in *2020 IEEE Frontiers in Education Conference (FIE)*, 2020, pp. 1–9.

[52] M. Haack and T. N. Jambor, "Investigation of variables related to university drop-out in problem-based learning," in *2020 IEEE Frontiers in Education Conference (FIE)*, 2020, pp. 1–8.

[53] ——, "Evaluation of a learner-centered activating learning situation with large cohorts in the university," in *2021 IEEE Frontiers in Education Conference (FIE)*, 2021, pp. 1–9.

[54] C. Gießer, J. Schmitt, M. Limbach, J. Otterbach, and R. Brück, "Skillslab+ - proof of concept for medical augmented reality teaching application with haptic feedback," in *2023 IEEE Global Engineering Education Conference (EDUCON)*, 2023, pp. 1–5.

[55] B.-M. Block, B. Haus, T. von Geyso, and A. Steenken, "Remote labs in electrical engineering to address heterogeneous student competencies in undergraduate engineering education," in *2023 IEEE Global Engineering Education Conference (EDUCON)*, 2023, pp. 1–7.

[56] M. Sandner, T. Uelzen, S. Yang, and P. Meier, "Dynamically configurable remote laboratory for electrical engineering education," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 01–05.

[57] M. Sandner, P. Meier, T. Uelzen, and S. Yang, "Java-based virtual laboratory for educational purposes in basic electrical engineering," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 1–5.

[58] S. Jaschke, T. Riehle, S. Jacobs, and M. Menzel, "Human-centered observation of learning processes in industry using augmented reality," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 1–5.

[59] I. Gross and I. Gross, "Take home lab as a chance for practical experience and problem based learning in a remote working situation," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, 2022, pp. 339–343.

[60] M. Haack and T. N. Jambor, "Influence of problem-based learning on student performance," in *2020 IEEE Global Engineering Education Conference (EDUCON)*, 2020, pp. 295–299.

[61] B. Konrad E.R. and A. S. Behr, "Teaching fluid mechanics in a virtual-reality based environment," in *2020 IEEE Global Engineering Education Conference (EDUCON)*, 2020, pp. 1563–1567.

[62] J. Haase, "Flipped classroom with digital circuits: An html5-based interactive simulation tool," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, 2022, pp. 307–312.

[63] F.-F. Salimi, F. Salimi, H. Taghipoor, R. Mokhtarname, A. A. Safavi, and L. Urbas, "Active learning on the collaborative digital twin of the process plants," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, 2022, pp. 878–883.

[64] F. Kreß, V. Sidorenko, I. Topko, K. Unger, T. Harbaum, and J. Becker, "Vhdl crash course: A multimedia-based teaching approach," in *2024 IEEE 3rd German Education Conference (GECon)*, 2024, pp. 1–6.

[65] A. S. Behr, L. M. Neuendorf, P. Sakthithasan, K. E. Boettcher, and N. Kockmann, "Process control using ai on a digital twin of an extraction column in vr," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[66] K. Kastner *et al.*, "Evaluating the effectiveness of avatar-based collaboration in xr for pump station training scenarios," in *2024 IEEE 3rd German Education Conference (GECon)*, 2024, pp. 1–7.

[67] F. Liegmann, L. Schorge, M. Kelker, and J. Haubrock, "Virtual reality grid control station for learning the operational management of real electrical grids on emergency situation," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[68] F. Püschel, D. Čubela, K. Böhm, and P. Neis, "What's the deal with cg? the usage of mixed reality applications as a means to facilitate meaningful experiences in teaching and learning computer graphics," in *2023 IEEE 2nd German Education Conference (GECon)*, 2023, pp. 1–6.

[69] L. Kobras, B. Meussen, and M. Soll, "Didactic design of a remote collaborative robotics laboratory," in *2023 IEEE 2nd German Education Conference (GECon)*, 2023, pp. 1–6.

[70] C. Bunse and T. Wieck, "Experiences in developing and using a remote lab in teaching robotics," in *2022 IEEE German Education Conference (GeCon)*, 2022, pp. 1–6.

[71] 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 Transactions on Education*, vol. 63, no. 3, pp. 198–208, 2020.

[72] I. Dunmoye, O. Olaogun, N. Hunsu, D. May, and R. Baffour, "Examining the predictive relationships between presences of a community of inquiry in a desktop virtual reality (vr) learning environment," *IEEE Transactions on Education*, vol. 67, no. 3, pp. 343–350, 2024.

[73] F. Bajraktari *et al.*, "A serious gaming approach for teaching environmental entrepreneurship," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, 2021, pp. 1310–1317.

[74] M. Soll, H. Helmken, M. Belde, S. Schimpfhauser, F. Nguyen, and D. Versick, "Building an it security laboratory for complex teaching scenarios using 'infrastructure as code'," in *2023 IEEE Global Engineering Education Conference (EDUCON)*, 2023, pp. 1–8.

[75] C. Drieschner *et al.*, "Teaching the concepts of servitization using a serious gaming approach," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, 2021, pp. 1537–1545.

[76] B. Levkovskyi, M. Bondarenko, M. Ring, G. Strimbu, M. Utesch, and H. Krcmar, "Toward a game-like experience: Design of a modern user interface of a simulation game for teaching business process

digitalization," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, 2022, pp. 1849–1857.

[77] A. Niedźwiecki, S. Jongebloed, Y. Zhan, M. Kümpel, J. Syrbe, and M. Beetz, "Cloud-based digital twin for cognitive robotics," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 1–5.

[78] D. Reith, P. Spelten, F. Rossbach, V. Lueddemann, F. Dieball, and G. Steinebach, "Bringing mathematical modeling and engineering students closer together by seamlessly linking theories, methods, and applications," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 1–8.

[79] A. Gruenewald, C. Giesser, S. Buechner, C. Gibas, and R. Brueck, "Going virtual: Teaching practical skills of circuit design and programming for heterogeneous groups online," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, 2021, pp. 404–412.

[80] B. Levkovskyi, V. Laurim, B. Kayaci, H. Mustroph, M. Utesch, and H. Krcmar, "Teaching the digital transformation of business processes: Design of a simulation game of business process change," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, 2021, pp. 1262–1271.

[81] M. Bondarenko, I. Kudryk, B. Levkovskyi, M. Utesch, and H. Krcmar, "Learning by gaming: Improvement of user experience of a simulation game for teaching the digital transformation and its administration cockpit," in *2022 IEEE Global Engineering Education Conference (EDUCON)*, 2022, pp. 1858–1867.

[82] T. J. Eiler, V. Schmücker, C. Gießer, and R. Brück, "Virtual and augmented reality for digital medicine - design and implementation of a hybrid, interdisciplinary course for engineering and medical students," in *2023 IEEE Global Engineering Education Conference (EDUCON)*, 2023, pp. 1–9.

[83] E. Yigitbas, M. Schmidt, A. Bucchiarone, S. Bassanelli, and G. Engels, "Gamification- and virtual reality-based learning environment for uml class diagram modeling," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 1–10.

[84] J. T. Gómez, N. Spicher, and J. Haase, "Effective synergies at technical universities to actively promote stem at k-12 schools," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 01–07.

[85] A. Schaffland, C. Müller, and J. Schöning, "Promoting the digital transformation of stem education with the mechanical neural network, a physical model for future-oriented and student-centered ai education," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 1–10.

[86] M. Herget and U. Schwalbe, "Hands-on power electronics course - deep understanding by combination of simulation, calculation and practical measurements," in *2020 IEEE Global Engineering Education Conference (EDUCON)*, 2020, pp. 497–503.

[87] M. Riel and R. Romeike, "3d print your artifacts – 3d turtle geometry as an introduction to programming," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, 2021, pp. 1454–1461.

[88] D. Assante, C. Capasso, O. Veneri, M. Castro, S. Martin, and H. D. Mohammadian, "Internet of energy: new scenarios, opportunities, challenges and educational solutions," in *2021 IEEE Global Engineering Education Conference (EDUCON)*, 2021, pp. 1514–1520.

[89] A. Calvo-Morata, N. Humble, P. Mozelius, R. Pechuel, and B. Fernández-Manjón, "Games for coding to attract new students to stem," in *2024 IEEE Global Engineering Education Conference (EDUCON)*, 2024, pp. 01–08.