Usability and User Experience Challenges of Cross Reality Laboratories Experienced by Creators

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Cross reality laboratories are widely used in education, yet research on the usability/user experience (UX) of these laboratories is still lacking. This study wants to start the discussion about challenges for usability/UX by interviewing practitioners from a large project for cross reality laboratories spanning multiple institutes in Germany. A total of 18 challenges were discovered, together with three target groups, namely, developers, maintainers, and learners. In addition, the tension between developers and usability is discussed. Open questions include the need to conduct further research with different target groups and how to increase usability for laboratory developers.

Keywords: Cross reality laboratories, Expert interview, STEM education, User experience

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1 Cross Reality Laboratories and Usability

Laboratories in general play an important role in Science, Technology, Engineering, Mathematics (STEM) education [1]. Here, a laboratory may refer to any teaching-learning activity that is intended to familiarize students with practical aspects of their field and allow them to test their acquired theoretical knowledge in applied contexts. As an alternative to classical, hands-on laboratories where students all partake in the teaching unit in a physical room, usually at the same time, cross reality laboratories can be used. Cross reality laboratories, as discussed in this paper, include take-home laboratories, augmented reality laboratories, remote laboratories, ultra-concurrent remote laboratories, and virtual laboratories [1]. All these different types of laboratories have in common that students are not confined to work in a designated place at a designated time but instead are scaffolded by different opportunities that learning technologies can offer. For example, in an augmented reality laboratory, the information students receive about any given physical laboratory setup is enhanced by additional virtual information delivered through devices like smartphones or special glasses. Ultra-concurrent laboratories make use of pre-recorded videos and accompanying experiment data to allow students to run different combinations of parameters that are valid for a given laboratory. This allows students to receive real laboratory results without actually interacting with the physical laboratory hardware. Cross reality laboratories, in general, can achieve learning success similar to or even better than traditional laboratories, e.g., see Brinson [2] for remote laboratories. Furthermore, these laboratories can also prepare students for Work 4.0 [3, 4].

The field of usability addresses the analysis, design, and evaluation of user interfaces for and user interactions with products/systems/services, thus enhancing the user-friendliness, efficiency, and satisfaction for different user groups thereof. In addition, user experience (UX) addresses the emotions, perceptions, as well as physical and psychological responses a user might have when interacting with a product, system, or service. Usability evaluation of digital teaching tools, e.g. for e-learning/learning management software [5], is not uncommon. However, the situation for usability of cross reality laboratories seems different. There are some papers discussing the usability of cross reality laboratories, e.g., [6–8]. However, a survey on papers from the ACM Digital Library and IEEE Xplore in August 2023 showed that these papers are in the minority and to the best knowledge of the authors, no paper has discussed the general usability challenges of cross reality laboratories.

The goal of this study is to facilitate the understanding of the challenges of usability/user experience (UX) for cross reality laboratories. To do this, the experiences from the CrossLab project [9], a large research project creating cross reality laboratories across multiple institutions in

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Germany, were collected. For this, a total of ten practitioners were interviewed about the usability/UX challenges they perceived from their experience of developing laboratories and using them for teaching. All interviews were semi-structured interviews [10, p. 34] and conducted in German. All participants gave their informed consent. The interviews were first transcribed and then inductively coded according to Mayring [10].

2 Challenges Experienced by Practitioners

The issues that were uncovered during the interviews can be grouped into six categories, the content of which is outlined further below.

Three of these categories deal with the different groups of people that interact with a system, namely, the **developers**, the **maintainers**, as well as the **learners** of a laboratory. A single person can be part of multiple target groups, both simultaneously and during different times. Here, "developers" mainly focuses on technicians that take care of the necessary hardware/software prerequisites but may include any person involved with the creation of a laboratory, e.g., a teacher that creates the teaching-learning material. While this paper deals with the technical perspective of laboratory development, another perspective one should not overlook but was not mentioned in the interviews is laboratory pedagogy. A laboratory may have multiple developers, and one developer may be involved in different laboratories, possibly even from differing perspectives. "Maintainers" means any persons involved with setting up the laboratory as part of the (established) learning infrastructure and keeping the laboratory running while not necessarily focusing on development work. "Learners" are the consumers of a laboratory, usually students from all walks of life in both formal and non-formal education settings.

Another two categories deal with general topics: **general issues of cross reality labs** on the one hand and general **UX guidelines** on the other.

The last category deals with challenges that do not focus directly on usability/UX issues but consider more the embedding of usability/UX in the **life cycle** of a cross reality laboratory.

2.1 Target Group "Developers"

The codes grouped into this category all deal with issues a developer of a (new) laboratory faces. A developer is, as stated before, any person that is actively involved in the development, enhancement, or design of a laboratory unit. In the interviews, only technical aspects of development were mentioned. Developers themselves encounter a number of difficulties while creating cross reality laboratories, some of which are usability problems developers encounter themselves. This is evident in the codes described below. Mitigating those hurdles might make it easier for developers to create laboratories and thus increase their quality or reduce costs.

1. **Functions are not properly documented:** Both hardware and software components may have flaws in their documentation from the very beginning, e.g., incompleteness, wrong data, translation issues. Additionally, documentation may become outdated over time, e.g., development of software continues but documentation is not kept up to date. This makes using third-party tools like software libraries or hardware parts difficult as developers have to invest more resources into figuring out how these tools work, which in turn means less resources for the actual development of the laboratory. This leads to the double-sided problem of "I can't use this" (usability issue) as well as "I don't want to deal with this" (UX issue).
2. **No "one size fits all" approach for user interface (UI) design:** Every application has its own set of interactions that need to be addressed. This includes both the selection of components for the UI as well as the components themselves. For example, if an industrial machine should be converted into a virtual laboratory, it might be necessary to design new UI components so they closely mimic the real-world machine. Therefore, a good UI needs to be tailor-made according to the needs of a specific laboratory while still respecting best practices of UI design.
3. **No tools for easy good optics:** A good UI does not only depend on the correct choice of components, but the visuals of the UI should also be pleasing to look at. This is even more important if custom layouts or components are used. Like linters or formatters for source code, common guidelines [11], practical guides [12, pp. 271], or "bad smells" [13] for UI design certainly exist. However, since developers are often not experienced designers, the application of said guidelines to a concrete interface is a laborious task developers cannot or do not want to perform. In our experience, developers would prefer to have a simple solution to provide pleasing visuals, e.g., a library, for UI so they can focus on technological development; for a pithy Python representation: `from libdevtools import nice_to_look_at`.
4. **Non-fitting components:** If by chance developers find a (non-)UI component they can use in the development of their laboratory, e.g., a third-party software that can be applied to remotely control the laboratory's hardware, these components are oftentimes designed for different, possibly non-pedagogical use cases. Thus, more effort needs to be put into making the laboratory work properly with the component, and learners may face a higher degree of difficulty when the developer confronts them with software designed for expert use. An example of this would be the use of commercial software to program robots which is not easy to apply for students with little to no experience in robot programming.

2.2 Target Group "Maintainers"

Maintainers are the people in the role of having to keep the laboratory running after it has been developed, and to patch enhancements or new features the developers hand them into the running laboratory instances. As such, the people in these roles do not necessarily have intimate knowledge of the development process or architectural specifics of any given laboratory, making it difficult to figure out very specific issues with the setup of such a laboratory. The interviews uncovered only a singular aspect pertaining to this target group, which in itself speaks volumes about how invisible this group seems to be. Thus, more research here is needed.

5. **Ease of use for IT administration:** Maintainers lack specific knowledge about the set of laboratories they are responsible for integrating. It is thus imperative to make setting the laboratories up as seamless as possible for the persons conducting the setup. This might include, but is not necessarily limited to, providing containerized software, setting up proper build and deployment processes in the laboratory, keeping the documentation up-to-date, providing sample configurations, or even a collaboration between developers and maintainers to be able to address each other's needs in a timely fashion and share required knowledge. In other words: Developers must speak the language and understand the tools of maintainers such that maintainers feel that "I can maintain the laboratory" (usability) and that they also feel that "I want to maintain the laboratory" (UX).

2.3 Target Group "Learners"

Oftentimes at the center of attention in education research, the learners are any people that interact with a laboratory in order to increase their own knowledge/skill/competences. As such, their issues regarding usability and UX stem from an entirely different perspective: learners are not sure what they are supposed to do, they do not have expert knowledge on how to handle the laboratory materials, and every learner has a different starting point for their laboratory "journey". However, as no learners were interviewed, the issues that were uncovered in the interviews should be taken with a grain of salt; see also item 12.

6. **Difficulties using controls:** Based on the experience from multiple cross reality laboratories, interviewees reported that students often had problems using "simple" systems. This might be because students have different backgrounds and knowledge based on what technical systems they have used before. For example, navigating a virtual avatar using the keyboard buttons *w (forward)*, *a (left)*, *s (backward)*, and *d (right)* might be easy and intuitive for someone with lots of experience in, say, computer gaming. Such a control schema might be overwhelming for someone who does not normally interact with virtual worlds. There seems to be a correlation between the course of study and the ability to control systems, e.g., someone studying computer science might adapt easier than someone studying chemistry. Further studies are warranted here, however.
7. **"Blame the system":** One interviewee observed that when using a more abstract system, e.g., a simulation or remote systems, users tend to search for errors in the system instead of in their own work. Students tend to blame the system for their own mistakes, so to speak. This can also be found in literature, e.g., [14].
8. **Special needs:** Special care should be taken of students with special needs. Cross reality laboratories can be seen as both an additional hurdle and an opportunity. On the one hand, digital laboratory systems can introduce new challenges for students with special needs, e.g., to connect cables, one has to click on a screen which might be hard or even impossible to do for students with visual or movement impairment. On the other hand, laboratories can be made available to these students that were previously not accessible, e.g., a laboratory in chemistry which requires quick reaction times might be made accessible through a simulation without danger to students. In general, a laboratory should be completable by everyone, despite disabilities or special needs, although this might not be possible for every laboratory.
9. **Different technical resources:** Only a couple of years ago one might assume a learner to use a PC with a reasonably large screen, workable speakers, and mouse/keyboard input. Nowadays, learners interact with learning and learning material through a host of different devices. While PC and/or laptops are still in use, classrooms oftentimes also see the use of tablets or smartphones. Some learners do not even own traditional computing devices anymore and are dependent on functioning touch controls. In the near future, we may also see learners accessing learning materials via virtual reality (VR). As such, laboratories have to consider the different devices and interaction methods learners might use.
10. **Different prior knowledge:** Learners come from different backgrounds and different walks of life. This is true in formal education, where, e.g., students of computer science may have different amounts of prior programming experience, but even more so in non-formal education or life-long learning settings where almost no assumptions about learners can be made. Hence, laboratory development should endeavor to not only make the knowledge prerequisites of a laboratory transparent but also to pick up the learners from their specific starting point, e.g., by giving explanation to technical language. Cross reality laboratories can even help here by making invisible processes visible, e.g., show the pathline/streamline/streakline and their difference in a fluid pump experiment [15].

2.4 General Issues of Cross Reality Labs

Laboratories are usually employed to deepen or support the teaching of certain knowledge/skills/competences. While canons for learning outcomes for laboratory education exist, see [16], it is also well-known that virtual laboratories are limited in the degree to which they can convey these learning outcomes. For an in-depth discussion on this topic, see [17]. This, in combination with taking away the experience of physically standing in the laboratory space and physically interacting with the apparatus, results in the following item.

11. **Cannot replicate holistic learning experience:** Laboratory learning is not only a cognitive experience, but also fosters competences that transcend the content of the laboratory. A traditional laboratory consists of more than the apparatus learners are supposed to interact with but also includes sensory experiences: the haptics of a robot arm, the texture of a work piece, the sound and smell of a workshop. These aspects and experiences are hard to replicate, e.g., in a virtual laboratory. This not only takes away from the learning process but also diminishes the learners' preparation for later when they have to work with the same or a similar apparatus on a company shop floor, e.g., see learning outcome "sensory awareness" in [16]. Care should be taken in creating a close-to-reality experience when building a cross reality laboratory.

2.5 General UX Guidelines

We were able to identify three general rules-of-thumb from the usability/UX perspective in our interviews that one should keep in mind while developing a laboratory, which are described here. These are not specific to cross reality laboratories but apply to them in particular.

12. **"You are not the user":** Calling back to some of the "Learners" issues, i.e., items 8 and 10, one needs to remember both during development and during testing of a laboratory that they are not the end users of the product. Generally, the prior knowledge of learners differs from that of developers. This is also true for the topic of the laboratory. For example, the result of a process may be evident to the teachers but not necessarily the learners. Since learners do not have the same knowledge or experience pertaining to the use of and interaction with the laboratory, they will probably behave differently and try other approaches than were intended. This can lead to frustration on the side of the learner in the sense that the laboratory interface does not behave like it supposedly "should", or that learners cannot figure out what they are supposed to do, see item 6. Furthermore, unanticipated actions in front of interfaces that were not properly tested can result in undefined system behavior. In the best case, undefined behavior can lead to more frustration, e.g., due to crashes. In the worst case, undefined behavior might result in dangerous side effects, e.g., mixing liquids that were not supposed to be mixed or unexpected robot movement. All this is to say that for proper laboratory usability and UX, efforts need to be made to consider the different starting points and mental models of the actual users.
13. **UI must cover all use cases:** Conversely, a laboratory oftentimes offers a lot of freedom in interacting with it. If a laboratory is offered virtually or in cross reality, special care should be taken with the interface specification to not only replicate the core features of a laboratory but to offer as much of the original freedom as possible. For example, a robot arm might be fitted with a gripper, and the task might be to palletize work pieces. An intuitive approach to a virtual offer might be to simply submit target poses for the robot and be able to control the opening and closing of the gripper. However, with a physical robot, learners might be able to experiment with freedrive, thus gaining a feel for how the robot moves and handles, as well as being able to configure speeds and forces. A cross reality laboratory should strive to mimic as much freedom as possible to approximate the natural learning experience as closely as possible.
14. **No "one size fits all" approach available for UX testing:** There are many methods for UX testing, such as target group analysis, questionnaires or observation studies. However, each method can only give a limited view into the usability of a laboratory, especially if, during testing, not all possible user groups are available. In addition, each method has its own associated resource investment. Therefore, while all methods are valid, the selection of UX tools is specific to the context of a laboratory in order to get good insights.

2.6 Life Cycle Issues

Some of the challenges do not concern a single cross reality laboratory, but instead take the whole process of integrating/increasing the usability/UX of a laboratory into consideration, i.e., creation, usability testing, usage by students.

15. **Low to no priority for UX during development:** Developers have many problems during the development of a cross reality laboratory, usability/UX being only one among others. Due to budget restrictions, time restrictions, or personal interest, usability/UX might not be put on high priority or might not even be considered during prototyping/early development. Since redesigning a system for usability/UX later is more costly, most systems stick to their initial design despite usability problems.
16. **Expert blindness:** Experts and students have different requirements, e.g., students might not know all the technical language and expert uses. Therefore, it is important

to ensure that all components of a system are designed for students. This is especially important when already existing components like standard software or complex simulations are employed, as these are often designed with experts in mind.

17. **Usability never properly tested:** Similar to item 15, but this item goes one step further: Many systems are used productively in teaching despite never being tested for usability. Since usability testing can reveal problems that developers do not know, see [18], this is unfortunate.
18. **Consider the whole learning environment:** When talking about cross reality laboratories, it is easy to only look at the technical systems. However, both usability/UX must be viewed at a wider angle: When used in teaching, the whole teaching environment must be considered. Questions might be: How well is the laboratory integrated into different learning material, especially into digital material? Does the laboratory help understanding? Does it address the correct learning outcomes? For an overview of laboratories in education, see [1].

3 Conclusion

This study gives a first glance into the usability/UX of cross reality laboratories. We were able to present a total of 18 challenges for cross reality laboratories just based on the experience of ten practitioners. Readers should keep in mind that this list is most likely incomplete, since this is not an in-depth usability study, missing, e.g., target group analyses. In addition, the scope of this study is limited, since only cross reality laboratory developers were interviewed; it would be useful to also include other target groups such as maintainers and learners.

Six categories of challenges were identified:

1. *Target Group "Developers":* These challenges chiefly pertain to the persons involved with developing a cross reality laboratory from its inception until its completion.
2. *Target Group "Maintainers":* One important discovery was the target group of maintainers. This group seems to be rarely researched.
3. *Target Group "Learners":* These challenges shed light on issues the consumers of a cross reality laboratory may have to deal with.
4. *General Issues of Cross Reality Labs:* The one challenge identified here is that the experience of a laboratory should be as holistic as possible.
5. *General UX Guidelines:* Some ground truths from UX research were also detected which apply to cross reality laboratories in particular.
6. *Life Cycle Issues:* Some of the identified issues, which are grouped here, do not specifically apply to any one instance of a cross reality laboratory but are related to the whole development process in itself.

The issues found here are especially relevant to cross reality laboratories. This shows that, while general guidelines might be useful, cross reality laboratories face their own usability/UX issues. Therefore, we would suggest not only intensifying the research about usability/UX, but also the development of specific tools/guidelines for usability/UX in cross reality laboratories.

The wish for such tools was also identified as one aspect during our interviews. Developers might not be aware of all usability problems [18]. This difference between the intent of designing good usability and actually doing it can also be observed in literature [19]. As a matter of fact, developers want handy tools for developing usable user interfaces that don not require expert knowledge. Of course, usability goes far beyond user interface design; however, we believe more automated tools to spot usability problems and to actually design user interfaces, e.g., predesigned components that can be used as-is, would help developers in designing more user-friendly systems.

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Abbreviations

UI user interface
UX user experience

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