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Designing augmented reality for makerspaces: Guidelines, lessons and mitigation strategies from 5+ years of AR educational projects

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ABSTRACT

Makerspaces are a relatively recent type of open-ended environment where users learn through authentic problem solving and interactions with peers. Augmented reality (AR) technology can improve learning and collaboration in such spaces, but it is unclear how one might design AR applications suitable for the physical, social and pedagogical richness of these environments. In this paper we present 5 research projects that explored the use of AR in makerspaces, covering various learning topics, physical configurations, and collaborative activities. We discuss lessons learned and distill these into 14 design guidelines. We conclude with a discussion of tensions to consider when designing AR for open-ended learning environments.

1. Introduction

Open-ended learning environments (OELEs) have been of interest to educational researchers and practitioners for decades (Hill & Land, 1998). OELEs provide a space that is process-oriented and student-centered (Hannafin, Hall, Land, & Hill, 1994), and allow students to collaboratively explore, experiment, and problem-solve while tackling projects that they are passionate about. Traditionally, this type of learning has been applied in university laboratories, industrial workshops, and entrepreneur innovation laboratories, where learners gain knowledge through authentic problem solving and interactions with peers, physical objects and equipment (Cevallos, Cedeño, & Gámes, 2020; Flanagan-Hall et al., 2018; Land, 2000; Weinmann, 2014). More recently, this type of space has been popularized in education and disseminated as makerspaces, where people construct physical artifacts as they are "developing a maker mindset" (Dougherty, 2011) by engaging in constructionist learning (Papert, 1980, p. 255).

At the same time, the technology of augmented reality (AR), which combines physical objects with virtual information, is being applied to educational settings, and showing potential to enhance learning and collaboration in open-ended environments (Arici, Yildirim, Caliklar, & Yilmaz, 2019; Beheshti, Kim, Ecanow, & Horn, 2017; Chang et al., 2022; Kim, Guida, & Kim, 2021; Radu, Hv, & Schneider, 2021; Radu & Schneider, 2019a). Due to the suitability of AR technology to support and enhance activities in makerspaces, we expect the number of AR applications to grow in these contexts (Radu, Joy, & Schneider, 2021). However, there are challenges associated with the development of AR applications, mainly due to the physical, social and pedagogical diversity and complexity inherent in such environments. The lack of guidelines will, at best, make it challenging to develop effective AR applications for such contexts or, at worst, will deter educators from adopting this technology (da Silva, Roberto, Teichrieb, & Cavalcante, 2016). In recent years multiple case studies of AR applications have been developed for makerspaces, including several from our research group. In this paper, we build on our research group's experiences designing and researching AR applications for makerspaces, as we describe lessons learned, provide guidelines for AR design in makerspaces, and discuss tensions for consideration by future AR designers. In the remainder of this introduction section, we first define makerspaces and related research in augmented reality applications and guidelines, and then we outline the contributions of our paper.

2. Literature review

Makerspaces are physical working spaces equipped with rapid prototyping tools (e.g., laser cutters, 3D printers, woodworking tools, etc.), where students of varying levels of expertise create physical objects. They bring together students with different levels of expertise, and support the development of skills such as collaboration, design, creativity, self-driven learning, and STEM technical skills. Recently, there has been a renewed interest in these spaces for their potential to promote 21st century skills such as critical thinking, collaboration, curiosity or creativity (Dede,

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2010). According to Hackerspaces.org and the U.S. Census Bureau, there has been a +14x increase in the number of maker spaces worldwide over the last decade (Lou & Peek, 2016). Although maker spaces are promising learning environments for empowering people to create personally meaningful artifacts while cultivating 21st century skills (Trilling & Fadel, 2009), such spaces suffer from challenges that may be solved with emerging technologies. One major limitation of maker spaces is that students focus primarily on doing (i.e., assembling a working prototype) and less on understanding. Dale Dougherty (Dougherty, 2011), a founder of the maker movement, highlights that makers as just *"playing with technology … They don't necessarily know what they're doing or why they're doing it."* While some learning does happen in such contexts, the majority of maker space activities are about following instructions or fixing problems, not specifically about deeper understanding or collaborative knowledge transfer. Additionally, makerspaces are messy environments where students follow different learning trajectories; it is a challenge for teachers and facilitators to monitor students' activities and provide scaffolding at the right time, and for students to maintain awareness of the different projects built by their peers. Such challenges may be solved through new technologies such as augmented reality.

There is increasing evidence that AR applications can improve project-based education in open-ended learning environments. AR has the potential to transform learning activities by infusing opportunities for learning, teaching and reflection, directly into students' iterative design process. For instance, AR was shown to improve understanding of electromagnetism physics (Ibáñez, Di Serio, Villarán, & Kloos, 2014; Radu, Huang, Kestin, Shah, & Schneider, 2022; Radu & Schneider, 2022), electronics (Beheshti et al., 2017; Reyes-Aviles & Aviles-Cruz, 2018), robots (Kyjanek, Al Bahar, Vasey, Wannemacher, & Menges, 2019, May; Radu, Hv, & Schneider, 2021), energy transfer (Fidan & Tuncel, 2019), design process (Kim et al., 2021; Wacker, Wagner, Voelker, & Borchers, 2018), and assembly (Song, 2020). These projects illustrate the potential of AR technology for learning with physical objects, and typically show that AR can lead to improved efficiency in performing tasks, reduced cognitive load, improved comprehension and collaboration. However, although such research investigations show the potential of AR technology in open-ended, collaborative environments, they typically do not provide guidelines for designing effective AR applications. The lack of design guidelines makes it expensive and time consuming to develop AR applications that are designed for this kind of complex, messy environment. One study estimates the cost of developing an AR application is between $50,000-$250,000 (Berman & Pollack, 2021), and the high cost of developing, testing, and supporting AR applications can be a barrier to the benefits of AR (Alam, Susmit, Lin, Masukujjaman & Ho., 2021; Berman & Pollack, 2021; da Silva et al., 2016).

In the current research literature, there exist no guidelines specific to designing augmented reality for makerspaces. Guidelines are lists of suggestions and considerations that exist to help designers create better products, and they are typically created from data collected through projects, prototypes and user studies, which then give rise to guideline patterns for effective design, which in time can turn into industry standards (Gabbard & Swan, 2008). Augmented reality guidelines have been proposed for designing applications in other AR domains, such as learning (Cuendet, Bonnard, Do-Lenh, & Dillenbourg, 2013; Dunleavy, 2014; Laine, 2018; Radu, 2014), navigation (Ko, Chang, & Ji, 2013), or tourism (Kourouthanassis, Boletsis, & Lekakos, 2013). Such guidelines typically cover multiple aspects of the user experience, ranging from generic usability to domain-specific considerations. Usability considerations include items such as designing for the physical characteristics of specific age groups (Radu, 2014; Tuli & Mantri, 2021); ensuring proper affordances and intuitive interface (Dünser, Grasset, Seichter, & Billinghurst, 2007; Ejaz, Ali, Ejaz, & Siddiqui, 2019; Santos et al., 2015); ensuring learnability and proper tutorials (Dünser et al., 2007; Ejaz et al., 2019; Radu, 2014; Tuli & Mantri, 2021); designing for natural gestures and manipulation (Endsley et al., 2017; Rose, 2021; Santos et al., 2015); designing mechanisms for tracking loss recovery (Radu, 2014; Tuli & Mantri, 2021). Some considerations exist for ensuring that AR is an appropriate technology for the task at hand, such as using AR to access phenomena difficult to see (Dunleavy, 2014; Rose, 2021), using AR not simply for its novelty (Laine, 2018; Radu, 2014; Rose, 2021), ensuring that tangible objects are augmented (Endsley et al., 2017; Rose, 2021), using AR to direct user attention (Rose, 2021), and ensuring that the visual design is not overwhelming (Endsley et al., 2017; Rose, 2021). Specifically in educational contexts, guidelines suggest that designers can use AR to visualize the unseen or spatially complex topics (Dunleavy, 2014; Radu, 2014; Rose, 2021), concretize abstract topics (Laine, 2018; Radu, 2014), use narrative and scaffolded problems (Dunleavy, 2014), leverage physicality (Laine, 2018; Radu, 2014; Rose, 2021), use AR to empower existing curricula (da Silva et al., 2016), use multiple types of representations to communicate learning content (Laine, 2018), support teacher awareness (Cuendet et al., 2013), or design for flexibility of classroom activities (Cuendet et al., 2013). Our contribution is to expand on these guidelines by investigating AR applications for makerspaces.

Makerspaces present specific challenges that require new types of guidelines: they have special requirements related to the large number of physical objects, informal social relationships, and the project-based nature of these environments. Although AR applications for makerspaces will benefit from some of the domain-independent guidelines listed above (e.g., designing for learnability and usability), new types of guidelines are also needed that cater for the specific characteristics of open-ended learning environments. In the present work, we address this research gap, and provide details about lessons learned, as well as guidelines and reflections generated through our research projects and their associated research studies, which explored how AR technology impacts learners in makerspace activities. In the following sections, we first contribute a description of AR applications designed for makerspaces along with the lessons learned from their design and evaluation; we then contribute a set of guidelines for addressing specific aspects of makerspace environments (in the areas of social, physical, cognitive, usability, and co-design). We conclude with a discussion of tensions to consider when designing AR for such learning environments.

3. Lessons learned from previous projects

This section describes projects and research studies that we have conducted in the last 5+ years. Our research team has been exploring various possibilities of AR applications for makerspace environments through the development of working projects involving headset-based augmented reality (i.e., Microsoft Hololens) and studied their effects through experimental studies in controlled laboratories and ecological settings. Through this process, we have documented the effects of AR technology on student learning, collaboration and affect, and we have accumulated a set of best practices for designing effective AR experiences. In this section, we describe the five projects developed over 5+ years (see appendix A for more information on each study). We then synthesize these findings into guidelines and tensions that designers should consider when developing AR systems in open-ended learning environments. To extract design principles, we followed the approach used by Cuendet et al. (2013): each guideline was formulated by reflecting on our personal experience as designers, feedback from users, qualitative observations and quantitative results from each study. To give readers a sense of the evidence was used for each guideline, we indicate our data sources in parentheses (QT: quantitative findings; QL: qualitative observations; PT: lessons learned during pilot studies; FD: user feedback).

3.1. HoloSpeaker - Supporting collaborative inquiry learning

The HoloSpeaker (Fig. 1) is an Augmented Reality (AR) experience that allows users to interact with the inner workings of a loudspeaker. The activity lets users assemble the different elements of a speaker (e.g., connect an audio source to a coil of wires that generates a magnetic

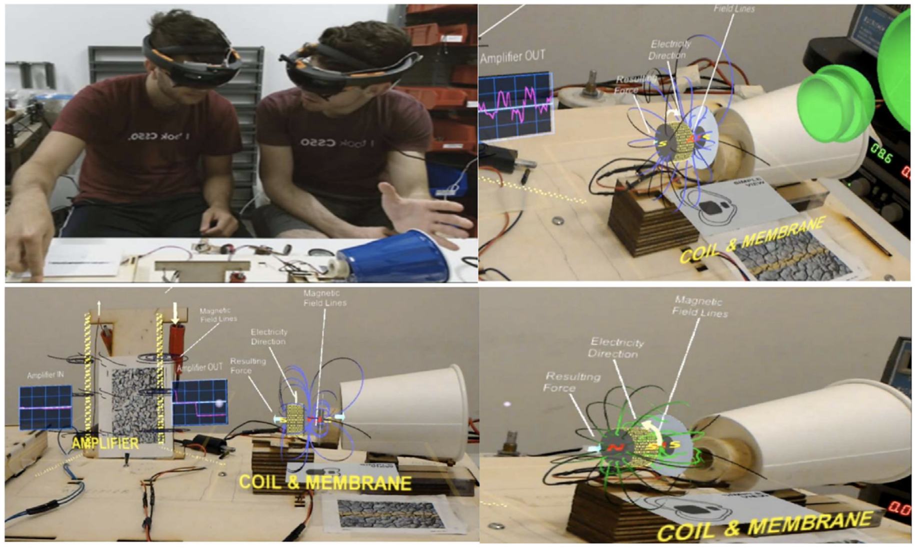

Fig. 1. The HoloSpeaker project allows collaborators to see invisible forces involved in a loudspeaker (i.e., how electrical signals produce magnetic fields, physical vibrations, and result in sound waves).

field), causing the magnet attached to a cup to vibrate and generate music. This AR layer makes invisible phenomena visible, such as the electrical current coming from the audio source, the magnetic field around the coil of wires, and the sound waves from the cup. In one study, we compared the affordances of this system for learning with a control group that had access to the same information, but provided by traditional mediums (e.g., paper, posters, compass). We found that participants in the AR condition were more engaged, participated more equally, learned more (especially when answering transfer questions), and improved their beliefs of self-efficacy toward physics (Radu & Schneider, 2019a; Radu & Schneider, 2019b; Radu & Schneider, 2022; Unahalekhaka, Radu, & Schneider, 2019; Tu, Radu, & Schneider, 2020). Some participants mentioned in the post-study interview that they would have considered a STEM career if their physics classes had used AR technology, which indicates a potential effect of AR on their attitudes. We also observed drawbacks from learning with AR: participants in the control group were better able to answer questions that involved kinesthetics (e.g., feeling the vibration from the cup), which suggests that AR can create a tunnel vision where users focus their attention on the AR content. Through an iterative design process that led to this study, we learned several lessons for designing effective AR experiences.

- AR can support collaborative learning by **making the invisible visible.** Participants performed better on some questions of a pre/post-test when they could see invisible phenomena. (QT)
- Balancing **how much information is provided** is crucial and **needs to be calibrated based on users' expertise**: pilot studies revealed that too much visual input can cause cognitive overload, and not enough information can cause confusion (because novices cannot make sense of the visuals - for instance, the shape of a magnetic field). (QT, PT)
- More specifically, our iterative process suggests that designers should strive to create AR experiences that are **minimalistic** (i.e., show as little information as necessary) but also **easily understandable** for example by providing labels, arrows and explanations to make complex visualizations understandable by novices. (PT, FD)
- If this tension is properly addressed, AR can positively influence not only learning, but also users' attitudes toward the content taught; for example, by increasing their confidence that they can learn complex concepts Since AR may increase confidence, designers should provide opportunities for **students to perceive complex concepts in intuitive ways.** (QT, QL)
- AR also seemed to facilitate collaboration: group members were more likely to participate equally when they could see the same digital content). We believe that **allowing multiple users to see digital content** and providing **shared access** makes it easier for novices to learn collaboratively. (QT)
- On the flipside, AR can also create a tunnel vision effect and hide learning content (physicality) because users neglect to pay attention to real-world changes. To avoid tunnel vision, designers should consider **avoiding visual overload**, allowing people to **turn on/off the visual layers**, designing the experience so people have to pay attention to the real world, or **progressively removing the AR scaffolding** so people can pay attention to the real world. (QT, PT)

3.2. HoloBot - Supporting collaborative programming

In the HoloBot project (Fig. 2) we investigated how augmented reality affects pairs of students as they collaboratively program a robot to navigate a maze. Light and proximity sensors were used to navigate the maze, and their values could be seen on a computer screen. With AR, the sensor values were also shown on the robot itself, along with sensor identification labels that made it easier to understand the location and function of individual sensors, and the values were dynamically changing as the robot moved in the maze. Early in the design process we experimented with showing pieces of the program overlaid on the AR sensors, but decided against it because the visual overlays were overwhelming. Through a user study, we compared student pairs as they either interacted with the robot in the traditional (non-augmented) way or using the AR overlays. We found that augmented reality significantly improved the learning of the participants located close to the robot (Radu, Hv, & Schneider, 2021). Since these participants were typically moving the robot and not watching the computer screen, AR improved their ability to understand how the program used sensor values while remaining continuously engaged with the robot. AR did not improve the learning of the participant close to the computer, likely because they already had access to sensor information on the programming interface. Furthermore, while analyzing the communication between peers, we found that AR improved collaboration by helping participants maintain a common ground and contribute equally to the problem-solving activity. In contrast, in the traditional non-AR condition, one participant typically dominated the discussion. The design lessons learned are as follows.

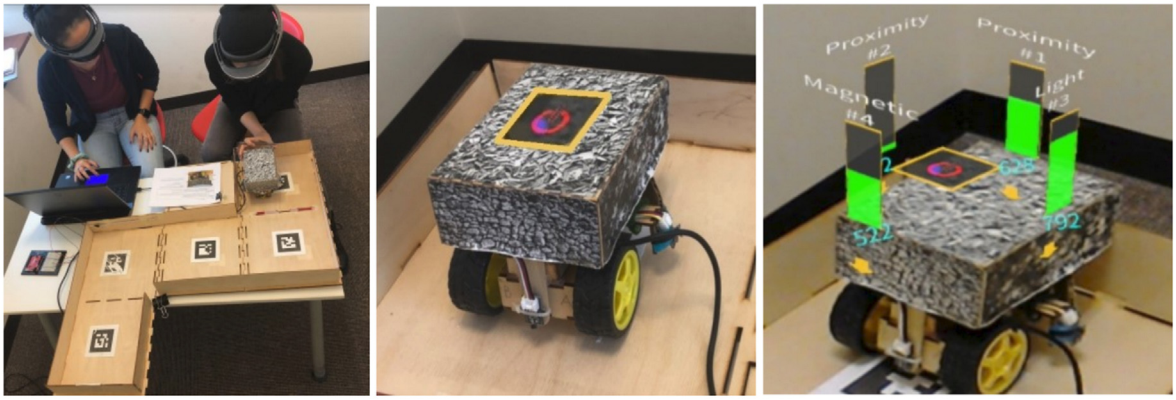

Fig. 2. The HoloBot project allows collaborators to view a robot's sensor values as they program it to navigate a variety of mazes.

- Users found the AR experience to be intuitive. This effect was achieved as we **designed for minimalism**; specifically, AR showed simple charts and not complex programs, and it required no interaction from the user. Thus, the application was effective because it was **easy to use,** and information was **intuitive to understand.** (PT, FD)
- The AR overlays **replicated information already available** on the computer screen. AR did not change the information but replicating it onto the robot was beneficial to participants who lacked access to that information. (QT, QL)
- The AR was **integrated into existing workflows**, by presenting information on the robot. Although this did not change user roles, it did improve feedback and the cycle of learning through acting on physical objects and led to improved learning and collaboration. (QT, QL)
- Similarly, it was important to **leverage what users already knew about the physical world** (e.g., their knowledge about manipulating physical objects like the robot) and have the AR visuals respond to that, rather than forcing people to interact with virtual elements. In makerspaces, this means designing AR that fits well with the physical objects and using sensors to create interactive visuals. (PT)
- Using AR was not useful for the user who was closer to the computer; however, it did influence the other user whose role tended to manipulate the robot. Thus, it's important to **consider individual roles**, and acknowledge that **AR is not necessary for everyone.** (QT, QL)
- In this study, AR empowered participants to contribute more equally. Thus, it is important to design AR for **enhancing individual understanding and participation.** (QT, QL)

3.3. HoloBoard – Supporting circuit debugging

The HoloBoard project (Fig. 3) was an ecological investigation of the added value of AR tools in makerspaces. We designed an augmented-reality holographic breadboard ("HoloBoard") which measures and displays electronic signals as holograms around the user's workspace. We deployed the HoloBoard tool in a summer semester course where fourteen students constructed electronics-enabled final projects and used tools to problem-solve their circuits (Radu et al., 2020a). While most students found the HoloBoard to be helpful, intuitive to use, interesting, user-friendly and effective, a significant number of participants did not take advantage of it. They mentioned that it was too complex for their projects because they were novices building simple circuits (Radu et al., 2020b). The Holoboard took time to set up, boot the headset, move their breadboard into the encasing, and read values; and they sometimes forgot how to use it because the tutorial came too early in the semester. In summary, we found that novices needed a tool that was more portable, easier to set up, and suitable to a wider variety of projects. These findings generated the following lessons.

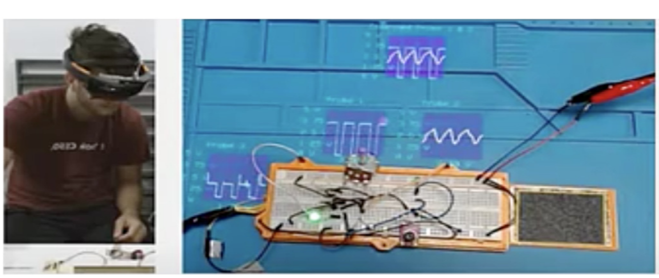

Fig. 3. The HoloBoards provides sensor visualizations around a user's electronic circuit.

- There is a cost to using any AR application, and people might not use it if it's not seamlessly integrated in their existing activities. In makerspaces, users already have existing workflows; thus, it is important that **AR applications fit into existing workflows.** (QL, FD)
- This case study suggests it is important to **provide flexibility in using AR to augment makerspace practices**, because there is a high diversity of projects. If the AR application is too specific (e.g., requires a special type of breadboard size), the cost of learning how to use it will outweigh its benefits and can result in non-use. (QL, FD)
- Designers should also be conscious to **reduce barriers to entry** by making the AR tools plug & play, and keep the learning curve low (i.e., make the system intuitive for first time users). (QL, FD)

3.4. HoloLenz - Supporting 1-on-1 online tutoring

The HoloLenz project (Fig. 4) is an augmented reality instructional tool that allows a physics instructor to hold 1on1 tutoring sessions with a remote student, for example to explain electromagnetism physics topics such as Lenz's Law. In makerspaces, this kind of 1on1 tutoring scenario is common; however, because of the COVID-19 pandemic, we are seeing more and more of this kind of instruction taking place online. Thus, there is a need to understand how AR can support conceptual understanding of physical phenomena in remote interactions. In the scenario explored in this study, the instructor and student are both connected through Zoom. The instructor wears a Hololens AR headset and interacts with physical objects such as a magnet and coil on their desk, while the student watches the instructor's view through Zoom screen sharing. As the instructor explains different topics, they can add/move/remove dynamic AR visualizations which respond to the movement of the physical objects, such as an overlay showing the magnetic field, a circular arrow that shows induced electricity movement, a graph that shows the changing strength of magnetic field in the coil, force arrows, etc. Through a user study, we compared how students respond to having the 1on1 tutoring session between two conditions: seeing the full dynamic AR visualizations dynamically changing on the magnet and coil or seeing a very basic set of

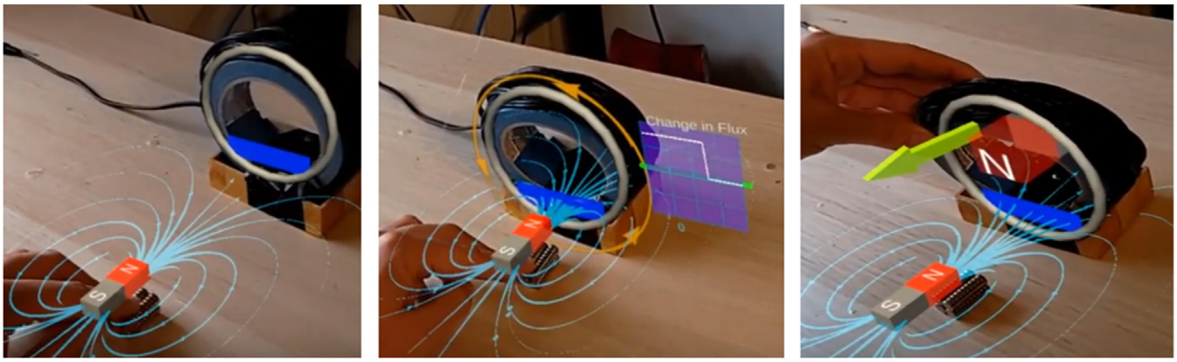

Fig. 4. The HoloLenz project enables an instructor to use dynamic AR visualizations while tutoring students about electromagnetism physics concepts.

AR visualizations (just a static current arrow on the coil, and a magnetic field located on the table not on the magnet). We found that the students who were tutored with full AR visualizations had higher learning gains, which included a better ability to transfer knowledge (Radu et al., 2022). Students used the AR visualizations as entry points for thinking about different concepts related to electromagnetism, and that AR visualizations functioned for conceptual linking and integrating multiple concepts together. Furthermore, students who saw the full AR experience showed more interest in taking actions, as observed by making significantly more requests for the instructor to take actions such as moving the magnet in different ways, likely because they were interested in seeing the reactions of the visualizations. Finally, the students who saw the reduced AR visualizations showed less variety in their inquiries and were more likely to be stuck asking similar kinds of questions, likely because they had more difficulty filling knowledge gaps than compared to the full AR group. The design lessons are as follows.

- AR visualizations acted as entry points for understanding different scientific concepts that were represented in the visualization. Thus, it's useful to **design AR visualizations that correspond to multiple different concepts**, and to ensure that the learning application **contains a variety of visualizations.** (PT, FD)
- Additionally, AR visualizations that are linked together can stimulate students to think more deeply about the links between scientific concepts. It's valuable to **design visualizations that are dynamically changing together.** (PT)
- As students observe visualizations that dynamically change in response to user action, they can become more active learners. It's valuable to **design mechanisms for learners to take action and observe feedback** (these can range from asking the instructor, or pushing a button, or reaching in to move the objects). If there are too many AR visualizations, the results can be overwhelming for students, so it may be important to **implement mechanisms for scaffolding the instructions** or **filtering the visual layers.** (QT, QL)
- Most visualizations were simple, but sometimes students did not understand what the visualizations meant. It's useful to **provide the ability for students to gain knowledge about what each representation means** (e.g., by enabling an informational layer, or asking questions to a helper) (FD)
- AR encouraged a richer diversity of inquiries. Some students wanted to learn the basics of concepts, then wanted to explore new situations, then asked about basic conceptual knowledge again. This hints that, when students experience educationally effective AR experiences, they may not follow a linear path as created by the instructional designer, thus it's important to **design for diversity of student inquiry styles.** (QL)

3.5. Supporting the co-design of AR prototypes

This ecological study involved co-designing AR applications with graduate students in a semester-long course about educational makerspaces. 18 students were enrolled, and were supported by one main teacher, two facilitators, and one makerspace manager. Throughout the semester, pairs of students collaborated with one researcher and one developer during brainstorming activities, prototype development, iteration, and summative evaluations. More specifically, each week, the students spent 30–45min familiarizing themselves with AR technology through reading material created by the researcher; they met with the development team for an hour to brainstorm AR prototypes that could enhance their project; the team then spent 1–3 days the AR prototype, based on the input from students; the prototype was then presented and evaluated in class by the audience; finally, the team met with the two students for a semi-structured interview to debrief on their experience (1h).

Multiple prototypes (Fig. 5) were developed to achieve a variety of end goals: using AR for visualizing the step-by-step process of how physical objects are constructed; explaining the unforeseen problems that arose during the construction of physical objects; helping students brainstorm different designs before actually creating them; explaining internal invisible circuits involved in electronic sensors; debugging computer programs while performing physical interactions; using AR to instruct users how a physical object works, and to attend to different parts of learning objects. Through the process of co-designing these prototypes, we generated an AR authoring environment available at (HGSE LIT Lab, 2022) that makes it easier for programmers to create multi-user AR applications that respond to signals from the physical environment. Furthermore, we created and evaluated ideas for AR in makerspaces, and generated considerations for integrating AR in open-ended learning environments. The students were excited about the co-design process: they felt they learned a lot about AR and co-designing technologies, they gained a voice/agency in creating technology, and became more critical about AR technology. Through this process the following lessons were formulated.

- AR can be an unfamiliar technology to many students, even more unfamiliar than VR. It's important to **dedicate ample time educating students about AR,** so that they can become familiar with the technology before brainstorming activities and during the iterative development process. (QL, PT)
- Students' prior knowledge matters a lot: they may have mistaken expectations of AR capabilities and may be overly optimistic or overly critical. Students need to be provided with materials that **familiarize them with what AR technology can and can't do**, and the

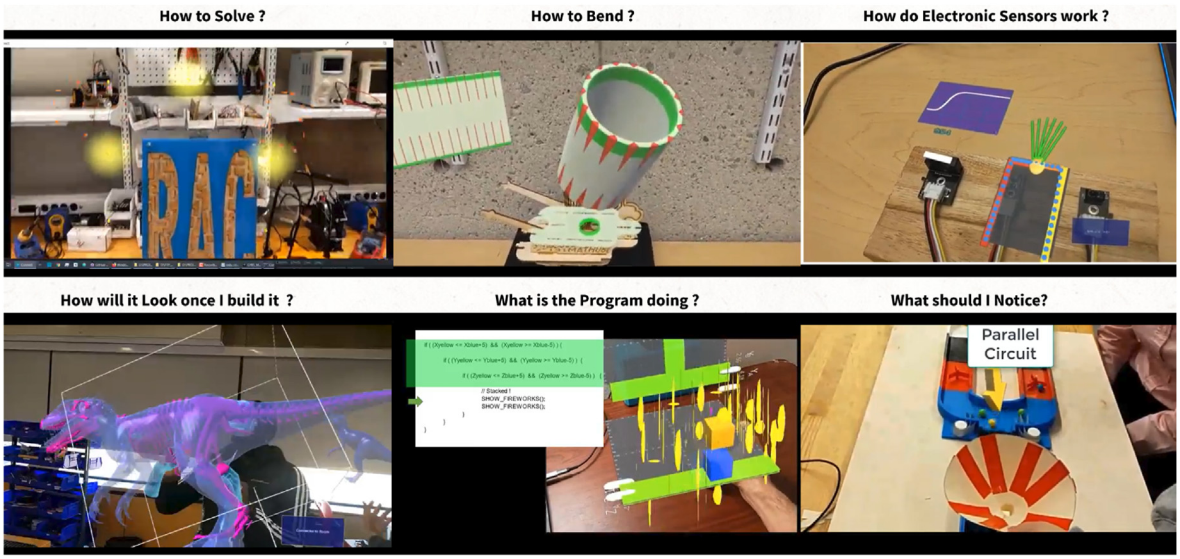

Fig. 5. Prototypes created in the co-design study, through collaborations with students.

developers will need to steer the brainstorming towards ideas that are feasible implementations within the course's time frame. (QL, FD)

- **Students don't need to be involved in all stages**, for instance students may not participate in software development, yet still feel they gain knowledge, agency, and critical thinking about technology. (PT)
- When creating AR learning presentations, **the presentation should be viewed by people unfamiliar with AR or unfamiliar with the project**, because viewers may be highly sensitive to aspects that developers don't mind (e.g., being sensitive to the jitter of the AR tracking, or being able to distinguish real vs virtual objects). (QL, FD)

4. Design guidelines

Through the process of developing these projects and researching their effects on users, we identified challenges that can inform the creation of effective AR applications for open-ended learning environments. In this section we synthesize lessons from these challenges into a listing of design guidelines, summarized in Table 1 and detailed below. Furthermore, we generated additional guidelines about structuring the process of co-designing AR technology (described in Appendix C).

Table 1
Listing of design guidelines.

SOCIAL COLLABORATION
Allow multiple users to simultaneously access content, and consider replicating existing information
Calibrate the experience based on users' roles and expertise
Understand for whom AR is not necessary
PHYSICAL INTEGRATION
Integrate into existing physical objects
Integrate into existing workflows
Design mechanisms for learners to take physical action and observe rapid feedback
CONCEPTUAL UNDERSTANDING
Provide various types of visualizations for different points of entry
Consider designing visualizations that are dynamically changing together
Visualize the invisible in relation to familiar objects in the physical world
Adjust the experience and scaffolding based on users' expertise, and design for diverse inquiry styles
USABILITY
Strive to be minimalistic, avoid visual overload
Provide explanations of what representation means
Reduce barriers to entry by leveraging what users already know
Dedicate ample time to educate users about what AR can or can't do

4.1. *Social collaboration guidelines*

Open-ended learning environments can involve collaborations between people who have varied interests, backgrounds and levels of expertise. Interactions between these variables influence what features and information should be built into AR experiences. Social interactions, for example, may be hierarchical where an experienced participant teaches a novice; or they may be collaborative, where team members work together to achieve a common goal. Furthermore, participants may work together in roles that are similar (e.g., both participants building a robot together), or highly specialized to their interests or expertise (e.g., one participant programming electronics and another participant constructing physical materials). When designing AR applications to support collaboration, we suggest considering the following guidelines:

Allow multiple users to simultaneously access content and consider replicating existing information: Having shared access to AR information enhances collaboration. If the workspace is relatively small, information can be made visible to all team members at the same time (e.g., the HoloSpeaker project). However, when the workspace is spread over a larger area, it may require duplicating information in different locations in proximity to each user (e.g., the HoloBot project).

Calibrate the experience based on users' roles and expertise: Depending on the activity, users might need to have access to different information. For instance, when an expert explains something to the novice, it is important that the expert has access to a set of complex AR representations and control when and how these are shown to the novice (e.g., HoloLenz project).

Understand for whom AR is not necessary: For some activities, the cost of using augmented reality technology may outweigh its benefits, and some collaborators may not actually need AR (e.g., HoloBoard and HoloBot projects). This applies, for example, when the team member has all the information available for their task without AR, or when the team member is doing activities that cannot be enhanced by AR.

4.2. *Physical integration guidelines*

Augmented reality visualizations provide value when they are integrated with the physical environment and responsive to users' physical actions. This is especially useful in open-ended learning environments such as makerspaces or experimental laboratories, where users interact with a variety of physical objects. A wide variety of objects can be augmented in a user's environment, ranging from large objects and machinery such as 3D printers, large robots and desk surfaces, to smaller objects such as electronics boards, hand tools, magnets, and measurement devices. Additionally, interactions can be highly varied, ranging from structured workflows such as multiple steps for using laser cutters; to unstructured workflows such as using hand tools ad-hoc during electronic circuit creation. In order to create AR experiences that are versatile for a variety of physical environments, we suggest the following guidelines:

Integrate AR into existing physical objects: Users will adopt technology more easily when it is seamlessly integrated into existing workspaces. AR experiences will be adopted easily when they do not require users to change the objects they are already using. For instance, by using computer vision to detect the user's objects without requiring additional sensors, or by using data from existing sensors (such as in the HoloBot project, where data was taken from the user's robot). This allows users to use existing objects without significant modifications, while leveraging the benefits of AR visualizations.

Integrate AR into existing workflows: Users may have workflows in place for dealing with physical objects and machinery. If AR tools require people to move to a different station or do things differently, they may not use it (such as in the case of the HoloBoard project, which required users to move their electronics to the AR workstation). Instead, designers should strive to understand existing workflows and design AR experiences that can be integrated into or simplify existing practices, rather than generating additional steps.

Design mechanisms for learners to take physical action and observe rapid feedback: When AR is integrated into existing objects, it can be designed to create a quick pathway for users to learn through interaction and feedback. For example, presenting information on the HoloBot project improved the cycle of learning through acting on physical objects, and led to improved learning and collaboration; similarly in the HoloLenz project, AR encouraged students to more actively engage and request actions to be taken by peers on the objects.

4.3. Conceptual understanding guidelines

Understanding complex phenomena requires students to comprehend multiple concepts and the relationships between them. Depending on the learning domain, students can vary in their familiarity with the concepts of the learning activity. Furthermore, the concepts themselves can vary in abstractness, and be represented in multiple ways, ranging from 3D animated models, to 2D representations, to simple text labels. Instructional designers may use augmented reality to vary the types of representations presented to students, as well as the timing and dynamics of how representations are integrated into the student activity. Based on our projects we present the following guidelines:

Provide various types of visualizations for different points of entry: One type of concept can be represented in multiple ways (for example, magnetic fields can be shown as 3D arrows, volumetric torus shapes, or vector fields), thus showing one concept in multiple ways gives students different points of entry to understanding that concept. Furthermore, our results suggest that students who see more visualizations representing different concepts (such as in the HoloSpeaker study) are stimulated to think about and discuss those multiple concepts. Thus, using multiple representations can encourage richer engagement with the learning content.

Consider designing visualizations that are dynamically changing together: Students need to recognize how the scientific concepts themselves fit together in an interlinked system, and how they function in relation to each other. We suggest designing AR environments where representations change together (for example by moving a magnet to control animations of force and current arrows, such as in the HoloLenz study), to facilitate intuitive understanding of relationships between the represented concepts.

Visualize the invisible in relation to familiar objects in the physical world: While AR visualizations can be displayed on empty surfaces, it is valuable to anchor AR content onto physical objects. For example, displaying magnetic fields on physical objects (HoloLenz project), or displaying voltage on real circuits (HoloBoard project). This enables learners to use their existing knowledge to understand relationships to AR visualizations and to interact with the learning content by manipulating familiar objects.

Adjust the experience and scaffolding based on users' expertise, and design for diverse inquiry styles: Students will enter the learning activity with different levels of background knowledge, so it is important to design scaffolding and instructional sequences that are adapted to the learners. This can be automatic if the system can detect what the user understands, or it can be user-driven if the AR system allows users to control the amount of scaffolding or the types of visualizations displayed at any given time. Furthermore, learners may have different interests, thus it is important to allow some degree of user freedom based on user interests.

4.4. Usability guidelines

Usability is the cornerstone of any learning experience; without good usability, students will lose motivation to engage with the learning content. While some modes of AR technology, such as smartphone AR, is becoming popular for users, other types such as AR headsets are still niche and require user training. Furthermore, the way of interacting with the AR content, such as screen-based interactions or hand-based manipulations, may be unfamiliar to users. Care must be taken to design seamless AR experiences:

Strive to be minimalistic and avoid visual overload. Visual overlays can be overwhelming and distracting, especially if displayed on physical or digital workspaces that are already busy. It is important to provide the right amount of AR visualizations to illustrate the core learning content that the users should focus on, and not more. When in doubt, designers can let students or teachers control what information is displayed, and filter unnecessary information (such as in the HoloLenz project where the instructor could add/remove AR visualizations depending on discussion topics).

Provide explanations of what the representations mean. Sometimes users may not be familiar with a visual representation or how to interact with it, and this may be difficult to learn especially if there is no instructor present. Designers can instruct users on how to read and use each representation, either by providing introductory tutorials or UI elements that allow users to gain further information.

Reduce barriers to entry by leveraging what users already know. Users will take knowledge from their interaction with other real or digital environments and transfer it to AR. Designers should strive to create AR representations that look familiar to users (e.g., in the HoloBot project showing sensors as 2D bar charts) and permit interactions that are expected (e.g., in the HoloLenz project, allowing the user to grab and move visualizations around the space).

Dedicate ample time to educate users about what AR can or can't do. Users may think they understand what AR technology entails, but they may have misconceptions about its capabilities, or may be thinking of related technologies like virtual reality. To provide a clear introduction, facilitators can walk students through existing example applications (through live demos or videos or student-downloadable apps) and focus on cases where the technology has limitations in detecting user-object interactions (e.g., inability to track objects, or inability to detect users picking up the membrane in the HoloSpeaker project), or issues due to environmental conditions such as poor lighting or lack of indoor tracking precision.

4.5. Co-design guidelines

In our research we generated some guidelines for the context where students co-design and create AR experiences. Co-design can be a powerful process of generating design ideas and prototypes by including students and other stakeholders such as teachers and facilitators, while at the same time increasing the participants' motivation, agency, and familiarity with emerging technologies. While the guidelines presented in this paper apply to structuring the design of AR learning applications, the following guidelines are about structuring the process of co-design.

Consider time constraints: The process of co-design requires ample time for stakeholders to engage in familiarization, brainstorming, prototype development, and evaluation. Multiple iterations may be required when developing prototypes, especially if creating complex designs or users are unfamiliar with the technology. If the co-design process is integrated into an existing process such as an academic course, special care must be given to differences in workload for co-design participants vs non-co-design participants.

Create a supportive environment and expect the unexpected: Co-design involves collaboration between stakeholders of different expertise, thus it is important to foster a respectful environment where multiple perspectives are valued. This is especially important when stakeholders are unfamiliar with technology and may offer ideas that are not feasible to implement, or when similar ideas already exist in other forms.

Provide knowledge of how to create effective AR experiences: Creating effective AR learning experiences requires knowledge about capabilities and limitations of AR technology, educational design, and usability considerations. When lacking such knowledge, stakeholders may suggest ineffective ideas; thus, it is suggested that stakeholders are provided with familiarization materials, such as examples of effective AR experiences, discussion of technology limitations, and exposure to guidelines (such as the ones listed above).

Stakeholders do not have to be involved in every stage of design: It is possible to hold a design process where the expertise of stakeholders is involved in the phases of ideas generation and of evaluation, but are not involved in the middle phase of prototype development. In this manner, stakeholders can offer insights at stages when their expertise is valuable, while reducing their time commitment.

Gather feedback from people unfamiliar with AR: Sometimes, lack of familiarity with technology can be beneficial because it stimulates ideas that are not constrained by current technological limitations. For example, we found that insights and ideas can come from talking to students and educators unfamiliar with AR, or from talking to children who provide unfiltered brainstorming ideas. Although such ideas may be often too undeveloped or impossible to achieve with current technology, sometimes they yield valuable stimulation for the brainstorming process.

5. Discussion

In this paper we have described various AR experiences designed for makerspace environments and the studies assessing their affordances. This allowed us to extract 14 design guidelines for creating augmented reality systems. Our guidelines provide recommendations on how to support social collaboration, facilitate integration of virtual content with physical objects, promote conceptual understanding, and increase usability. We expect these guidelines to support designers and help them make more informed decisions when considering the use of AR in various open-ended learning environments (e.g., not just in makerspaces, but also in factory settings, hands-on lab sessions, professional workshops, engineering contexts, and more).

The guidelines presented above share overlaps with guidelines created in other contexts; for example, with usability guidelines such as striving for familiarity, reducing barriers to entry, or providing information about what representations mean (Ejaz et al., 2019; Radu, 2014; Tuli & Mantri, 2021), as well as guidelines about educational and collaborative design, such as providing appropriate scaffolding, striving to visualize invisible phenomena, designing multiple representations, and designing for various user roles (Cuendet et al., 2013; Dunleavy, 2014; Laine, 2018; Radu, 2014; Rose, 2021). However, makerspaces differ from traditional environments due to their high diversity of social configurations, wide variety of physical objects, and multitude of educational content. Thus, our guidelines highlight considerations for AR designs that are especially salient for these environments. For example, makerspace users work with a variety of physical objects and workflows; it is important to have tracking mechanisms that integrate AR with different types of objects and cater to messy workspaces, as well as design AR activity workflows that match already existent physical fabrication practices. Additionally, makerspaces can benefit from AR applications that use sensors to monitor invisible phenomena and provide feedback in real-time as students manipulate objects while instructing, exploring or debugging their behaviors. It is also important for designers to create AR applications that adapt to different levels of student expertise and understand that situations exist where accessing an AR device is not necessary for some users. Finally, because makerspaces touch on many learning domains, AR designers are encouraged to design visual representations for various invisible phenomena that users may be interested in, and design interactive methods for linking the visual representations to allow conceptual understanding of interrelated concepts. These design considerations specifically apply for makerspace environments but may be extended to other open collaborative learning environments.

While these guidelines were formulated a posteriori, they resulted from challenges we encountered when designing AR experiences. These challenges were often the results of tensions we had to navigate as designers. In this discussion, we discuss issues that might arise when designers mishandle tensions, their consequences for the user experience, and mitigation strategies to avoid extremes that can be detrimental. Table 2 is a summary guide for AR designers. Each row can be used as a lens to assess whether the experience is well-balanced (e.g., in terms of the number of visuals, level of complexity, immersion, etc.) and how it could be improved using mitigation strategies.

The first and main tension we had to navigate was the **amount of AR visuals displayed**. Designers need to think critically about what is worth visualizing through AR as opposed to other mediums such as computer screens; anything that can be done on a computer screen, for example, under-exploits AR technology. Thus, when AR seems under-utilized, designers should consider making invisible information visible, especially information that can be difficult to visualize using other platforms, or difficult to connect with real-world phenomena. On the other hand, designers also need to be wary of showing too much information through AR. This may lead to visual overload or cause learners to be distracted and ignore some content. In this case, designers should strive to provide a minimalist experience while leveraging the medium of AR, or let users turn AR layers on/off to decrease visual clutter and cognitive load.

Another tension we encountered was **to adjust the level of complexity of the visuals**. This is a non-trivial consideration, especially when considering the task's characteristics and users' prior knowledge. In the projects described above, we found that users were easily confused by visualizations that they were unfamiliar with. For example, some of our participants struggled to make sense of magnetic fields represented as concentric circles because they did not have the prior knowledge to make sense of this representation. In this situation, consider using scaffolding to help users interpret the visuals, or use representations that they are familiar with. On the other extreme, a risk is to make the visuals too simple, so much that they don't add any educational value to what users already know. In various studies, we used control groups with simple AR visualizations to control for novelty effects. We often found an effect on engagement and motivation, but not on learning. For this reason, we recommend going beyond using AR to increase engagement and consider modeling complex phenomena that might be interconnected with physical or virtual events.

A third tension was **to calibrate the level of engagement** of the AR experience. AR has the potential to attract learners' attention, and deeply engage them. Designing an unstimulating AR learning experience is a wasted opportunity because AR can be highly engaging. We recommend the use of aesthetically pleasing, curiosity-grabbing, interactive visuals to increase immersion. On the other hand, one should also be wary of overly

Table 2
Design tensions and mitigation strategies.

Dimension	Issue	Consequence	Mitigation
AR visuals	Not enough	AR is underused	If there is interesting **invisible information, consider making it visible** - especially if that information is difficult to visualize using other platforms (e.g., computer display)
	Too many	Cognitive overload	Consider **turning layers on/off**, providing multiple points of entry, more **minimalist experience**
Level of complexity	Too simple	AR is underused	Consider using **multiple, interconnected visualizations** to highlights interactions between phenomena of interest
	Too complex	Causes confusion	Design for the **user's background expertise**; provide **scaffolding**; show more complex content as the user learns
Level of stimulation	Not enough	Decreases users' engagement	Consider using **more engaging, complex, interconnected, animated visuals** to engage users
	Too much	Tunnel vision	Provide cues to remind users to connect virtual information with physical stimuli; provide **different points of entry** for understanding the connection
User's agency	Too limited	Decreases agency and motivation	**Design for diversity of inquiry styles**, by giving more agency to users, by letting them decide what to explore
	Too open-ended	Users can get lost and confused	Consider giving more structure to users, by designing **scaffolding that can be turned on/off**
Object tracking	No awareness of physical objects	limited added-value from AR	either consider porting the same experience to a VR environment, or tracking objects to connect virtual information to the physical environment
Collaboration	No shared content	confusion about what the other can see	Consider **replicating existing information** by sharing the same content between users to facilitate building a common ground
	Some content is shared	discrepancies between users' experiences	**Enhance individual understanding and participation** (e.g., by giving individuals super powers to help the group)
	Duplicated content	Limited opportunity to contribute something new	Consider providing slightly different content for each user, so that they are encouraged to work together and contribute to the discussion

stimulating experiences. In our work, we found that this could create a "tunnel vision" effect and cause learners to neglect important information from the physical world (e.g., kinesthetic feedback, such as subtle movements or vibrations). In this case we recommend decreasing the amount of AR information, or using cues to direct users' attention to relevant non-AR information.

A fourth trade-off was **how much agency is given to users**. We found that when the experience was too controlled and linear, users lost motivation to explore the content taught. In our studies, users were naturally curious about the AR representations, and wanted some freedom to interact with them. On the other hand, giving too much freedom caused users to be disoriented and confused. A useful strategy for calibrating agency is to provide scaffolding that fades over time; for example, users can see hints on how to interact with the AR content or arrows to guide their attention, which fade over time. Another strategy is to design multiple pathways, so that students with different inquiry styles can decide how to explore the content.

A fifth consideration is **how much of the physical environment (e.g., objects) should be tracked.** Having no connection to the physical environment is often an under-use of AR capabilities (and such experiences may be more suitable to other mediums, such as VR). Too much connection is computationally intractable, because AR headsets have limited sensing capabilities and relatively weak processing power. Thus, designers need to make intentional decisions about what is sensed and how accurately the environment is being tracked. In the projects described above, we spent a great deal of time and energy tracking a few objects very well (e.g., magnets, coils of wire, robots, breadboard, etc.) so that we could overlay virtual simulations on them to facilitate understanding of complex phenomena.

A sixth tension was **to create shared AR experiences for groups of users**. Designers need to decide how much information is shared between users, and how it facilitates different types of interactions. When no content is shared, users have to explicitly and verbally describe the information they have access to. While this could cause disengagement and frustration, there are situations where this design decision could be beneficial (e.g., students participating in a jigsaw learning scenario, where they have to combine individual information to find a shared solution). When the content is duplicated, there is no risk for misunderstanding - but it may lead to a missed opportunity to engage each user in the activity. In sum, we encourage designers to consider sharing some, but not all, AR information among users. There should be enough shared information to facilitate building a common ground, but also opportunities for users to individually contribute to the experience. What is (not) shared should be the result of a conscious and intentional decision from the designers.

While the guidelines and tensions were helpful in the context of our research projects, we acknowledge that they are contextual and might not always be transferable to other situations (e.g., traditional classrooms) or different populations (e.g., younger learners). While designers can expect a certain level of technological and conceptual fluency from adults, children – and even teenagers – might require additional design considerations. For example, designers might need to consider the developmental stage of their users in terms of the level of abstractness/concreteness of the AR system and adapt the user experience accordingly. In other words, physical, cultural, societal, and demographical contexts matter a lot for effectively using AR; these guidelines and tensions should be applied differently depending on these factors.

Additionally, our guidelines are somewhat specific to the technology currently used in makerspace and for creating AR content. We do not know what AR technologies or makerspaces/learning environments will look like 10 years from now. Additionally, we based our guidelines solely on the work we conducted; these studies sometimes had small sample sizes, the majority were done in controlled settings, with similar users, and were led by the same research team. To generalize these results, researchers could use other published research to augment our guidelines, extend the results with larger sample sizes, replicate the results in other contexts, and/or conduct additional ecological implementations of these systems. Finally, we acknowledge that there are other guidelines that we did not explore and which could be covered by future work - for example, guidelines for facilitating social interactions in larger groups (e.g., community building), increasing accessibility and inclusion through remote AR experiences, working with other age groups (e.g., children or elderly), or exploring AR applications for topics that require longer-term exposure (e.g., 21st century skills). Future research can extend this work by refining these guidelines, adding findings from other studies, settings, and types of learning environments beyond makerspaces, and conducting longitudinal studies of AR uses in ecological settings, with more diverse populations. This will support the refinement of these guidelines, and potentially add dimensions that were not addressed here (e.g., AR for larger social groups, such as communities). Finally, future research can extend these guidelines to other forms of AR (besides headsets; e.g., phone/tablet-based, or using other types of wearables like smart glasses), to provide more comprehensive design recommendations.

6. Conclusion

While the guidelines and tensions described in this paper are context and project specific, it is a step toward formalizing the implicit design process that AR creators need to navigate. We hope that this can provide an explicit terminology for other researchers, so that design tensions can be more easily discussed and better understood. Finally, we encourage AR researchers to build upon these design guidelines, by applying them to other contexts, other populations and other technological settings, so that we can get a better sense of their generalizability.

Statements on open data and ethics

The data for this study is confidential and not available for open access. The study has approval from the university's Institutional Review Board and adheres to the institution's ethical guidelines. The participants participated voluntarily, and all data has been anonymized prior to publication.

Declaration of competing interest

We confirm that this work is original and has not been published in any other journal, and we have no conflicts of interest to disclose.

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Appendices.

Appendix A: Description of the Studies

Project	HoloSpeaker	HoloBot
N=	120	80
Participants	Participants were recruited from the study pool of a university in the northeastern United States. They did not have any prior experience using the Microsoft Hololens.	Participants were recruited from the study pool of a university in the northeastern United States. Ages ranged from 19 to 51 years old with a mean of 26.7 years, and 60% identified as female.
Method	Controlled study 2 × 2 design; Non-AR vs simple-AR; layered-AR vs Full-AR	Controlled study Conditions: AR vs non-AR
Main metric(s)	(Quantitative) Learning gains (pre/post-test) Knowledge exchange Collaboration quality	(Quantitative) Learning gains Collaboration quality Equality of contribution
Main Finding(s)	Compared to non-AR conditions, AR generated a novelty effect AR also supported conceptual learning, but hindered kinesthetic learning (tunnel vision) AR facilitated collaboration, by providing a representational common ground	Augmented reality improved overall group learning and collaboration. Easy access to AR visualizations helped both participants maintain a common ground and balance contributions during problem solving activities.
Related Guideline(s)	AR can support learning by making the invisible visible More specifically, it can help students perceive complex concepts in intuitive ways However, it is easy to overload learners with visuals Thus, it is important to balance how much information is provided Shared access makes it easier for novices to learn collaboratively	Designed for minimalism Leverage what users already know about the physical world Integrated AR into existing workflows Consider individual roles Replicate information already available to enhance individual participation

Appendix 1continued

HoloBoard	HoloLenz	AR prototypes
14	44	18
Participants were undergraduate students enrolled in a Summer digital fabrication course. They did not have any prior experience using the Microsoft Hololens.	Participants were undergraduate students enrolled in an introductory physics course. Age was average 23.5 (SD = 4.4; min = 19; max = 35) years, with genders: 28 female, 13 male, 2 nonbinary, and 1 did not disclose.	Participants were graduate students enrolled in a semester-long digital fabrication course (17 females, 1 male). Students' prior experience with teaching ranged between 0 and 7 years (M = 1.8; SD = 2.4). None of the students had prior experience with using or developing AR educational applications.
Ecological Co-design study	Controlled study Conditions: Full-AR vs Basic-AR	Ecological Co-design study
(Qualitative) Interviews Qualitative observations	(Quantitative) Learning gains Inquiry styles Verbal references	(Qualitative) Interviews Notes from participatory design sessions (Quantitative) Usability surveys
Students who used the tool had a positive experience They found the tool to be helpful for debugging circuits	Students who were tutored with more complex AR learned better; they showed a wider variety of inquiry styles They made deeper connections between scientific concepts,	AR technology can help teach STEM skills, facilitate construction activities, enhance contextualization of learning, and debug.

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(*continued*)

HoloBoard	HoloLenz	AR prototypes
Other students were hesitant to use the tool for reasons including lack of portability, disruption of workflow, and inability to fit non-standard breadboards.	AR encouraged students to have a more active learning style, with increased transitions between inquiry activities.	Students demonstrated improved understanding of technology design, enthusiasm for using AR Increased critical thinking about AR technology
Reduce barriers to entry Provide flexibility in using AR to augment makerspace practices AR applications should fit into existing workflows	Design AR visualizations that correspond to multiple different concepts Ensure that the learning application contains a variety of visualizations Design visualizations that are dynamically changing together. Design mechanisms for learners to take action and observe feedback Design for diversity of student inquiry styles.	Dedicate ample time to educate students about AR Familiarize them to what AR technology can and can't do Students don't need to be involved in all stages of the AR design process The AR prototype should be viewed by people unfamiliar with AR or unfamiliar with the project

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