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Charting opportunities and guidelines for augmented reality in makerspaces through prototyping and co-design research

Iulian Radu *, Josia Yuan, Xiaomeng Huang, Bertrand Schneider **

Graduate School of Education, Harvard University, 6 Appian Way, Cambridge, MA, 02138, USA

A R T I C L E I N F O

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A B S T R A C T

Makerspace environments are becoming popular project-based learning spaces where students interact with physical objects and peer collaboration, while developing 21st century skills and engaging with science, technology, engineering, and math (STEM) topics. At the same time, augmented reality (AR) technology, which combines physical objects with digital visualizations, is becoming increasingly applicable for makerspace activities and has potential to address challenges for student learning in makerspaces. However, there is a lack of understanding of how to use and integrate AR in real makerspace environments. In this research we use a co-design methodology to address the following questions: (1) How can AR be useful for education in makerspaces? (2) How are students impacted by the process of co-designing AR technology? and (3) What are practical considerations for integrating AR in makerspaces? We engaged in a co-design process in a semester-long makerspace course attended by 18 students in a graduate school of education. Through this process, we generated six prototypes with seven student co-designers, exploring AR use in design, fabrication, programming, electronics, and training. We also identified areas where AR technology can benefit makerspaces, such as teaching STEM skills, facilitating construction activities, enhancing contextualization of learning, and debugging. We observed that students participating in co-design demonstrated improved understanding of technology design, enthusiasm for engaging with makerspaces and AR, and increased critical thinking about AR technology. These results suggest considerations and guidelines for integrating AR technology into makerspace environments.

1. Introduction

In the last decade, the "Maker Movement" and a growing interest in teaching 21st century skills have increased the popularity of makerspaces, which serve as informal versions of project-based learning environments for science, technology, engineering, and math (STEM) education (Sharma, 2021). These spaces often include equipment such as laser cutters, 3D printers, and woodworking tools, and they provide a place for students of different skill levels to work together on projects that reflect their personal creativity and interests (Lee et al., 2019). Makerspaces are designed to support the development of important skills such as collaboration, design, creativity, self-driven learning, and technical expertise in STEM subjects (Martin, 2015; Rayna & Striukova, 2021), and provide a hands-on collaborative learning environment that is different from traditional classroom settings, as the pedagogical approach focuses on learning through student-driven projects rather than direct instruction (Peppler et al., 2016; Taheri et al., 2019). However, a challenge of learning in makerspaces is that students focus more on fabrication than conceptual learning, due to the difficulty of learning about invisible STEM concepts, the time-consuming nature of designing and fabricating objects, and the lack of personalized scaffolding and guidance from trained facilitators (Blikstein, 2013; Dougherty, 2011; Harron & Hughes, 2018; Lock et al., 2018; Radu & Schneider, 2019a).

There is increasing evidence that augmented reality (AR) technology, which overlays virtual visualizations on physical objects, can address these issues and improve project-based education in makerspace contexts. For example, AR can improve students' understanding of electronics (Beheshti et al., 2017; Restivo et al., 2014; Reyes-Aviles & Aviles-Cruz, 2018), robots (Kyjanek et al., 2019; Peng et al., 2018, April; Radu, Hv, & Schneider, 2021), physics (Radu et al., 2022,b; Radu & Schneider, 2019a), designs (Kim et al., 2021; Wacker, Wagner, Voelker, & Borchers, 2018, October), construction (Peng et al., 2018, April; Song,

* Corresponding author.
** Corresponding author.
E-mail addresses: iulian_radu@gse.harvard.edu, iulian@gatech.edu (I. Radu), jiayingyuan@gse.harvard.edu (J. Yuan), xiaomenghuang108@163.com (X. Huang), bertrand_schneider@gse.harvard.edu (B. Schneider).

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2020), and is generally useful in collaborative learning contexts (Phon et al., 2014; Wanis, 2019). Most explorations of AR for education have not been done in the context of makerspaces, but the increasing availability of AR-enabled devices such as headsets and smartphones, combined with the increased interest in using AR for education, is expected to lead to an increased usage of AR in makerspaces.

However, research on AR in makerspaces is sparse, and much remains unknown about optimal design and challenges that arise when integrating AR in these environments. Without this knowledge, AR application designers may create experiences that are ineffective or unusable by students in real contexts and can increase barriers for teacher adoption (da Silva et al., 2016). The current research investigates the potential usefulness and integration of AR in makerspaces by using a co-design methodology with students in a semester-long makerspace course, and addressing the following research questions.

RQ1. How can augmented reality be useful for education in makerspaces?
RQ2. How are students impacted by the process of co-designing AR technology?
RQ3. What are practical considerations for integrating AR in makerspaces?

In the remainder of this paper, we first present related work in the domains of AR education, makerspaces, and co-design. Then, we describe our research method, followed by results, guidelines, and broader discussion.

2. Related work

In this section we first introduce literature about the potential of augmented reality for education, and the potential and challenges of makerspace education. Then we present the growing research literature investigating how augmented reality can enhance makerspace activities, and we reflect on the need for further explorations and guidelines for integrating AR in makerspaces. Finally, we discuss how a co-design methodology can be used for exploring future uses of AR technology, while positively impacting students in current environments.

2.1. Augmented reality for education

We define augmented reality according to Azuma's (1997) criteria: AR is a technology that combines real and virtual content (e.g., showing a virtual graph of sensor data overlaid on a physical robot's sensors), is interactive (e.g., the virtual graph changes in real time in response to user interacting with the robot), and is registered in 3D (e.g. the virtual graph is displayed in 3D and remains anchored to the robot as it is moved in 3D space). This study focuses on augmented reality experiences that can be viewed on headset displays (such as the Microsoft Hololens), handheld devices (mobile phones or tables), and webcam-enabled computers.

Augmented reality can benefit educational outcomes in a variety of contexts (Akçayır & Akçayır, 2017; Arici et al., 2019; Garzón et al., 2019; Radu et al., 2022,a). For example, AR applications have been designed to improve learning of STEM domains such as physics (Lai & Cheong, 2022), chemistry (Mazzuco et al., 2022), astronomy (Gallardo et al., 2022; Önal & Önal, 2021), mathematics (Ahmad & Junaini, 2020), biology (Kalana et al., 2020); non-STEM domains such as language and literacy (Parmaxi & Demetriou, 2020), history (Challenor & Ma, 2019), social-emotional learning (Papoutsi et al., 2021); and to enhance other activities that may occur in makerspaces, such as design, collaboration and training (see Section 2.3 for discussion about AR for makerspaces).

Compared to traditional educational methods, AR applications can be more effective because they show 3D structures that are difficult to mentally visualize (Abdinejad et al., 2021; Wolle et al., 2018), visualize phenomena that are invisible with the naked eye (Beheshti et al., 2018; Radu & Schneider, 2019a), reduce physical and cognitive demand by providing learners with information in context of use (Buchner et al., 2022; Georgiou & Kyza, 2018; Lu et al., 2014), guide user attention and enhance focus (Mohr et al., 2017; Tosto et al., 2020; Yilmaz & Goktas, 2017; Zubizarreta et al., 2019), improve memory retention (Gargrish et al., 2021; Karagozlu, 2018; Lam et al., 2021), increase relevance and usefulness of learning content by situating it in physical contexts (Mohr et al., 2017; Nguyen et al., 2020; Radu & Schneider, 2019a; Yilmaz & Goktas, 2017), foster learner confidence and self-efficacy (Mohr et al., 2017; Radu & Schneider, 2019a; Schneider et al., 2016), facilitate collaboration and group dynamics (Radu & Schneider, 2019b; Schneider et al., 2016; Zhang et al., 2016), and generally improve curiosity, engagement and motivation (Arici et al., 2019; Bork et al., 2017; Villanueva et al., 2020; Zhang et al., 2016).

These affordances can be particularly beneficial in makerspace environments, where physical interaction and fabrication plays a critical role in student learning.

2.2. Makerspaces as educational environments

In open learning environments such as makerspaces, learning is process-oriented and student-centered (Hannafin, Hall, Land, & Hill, 1994; Hill & Land, 1998): students take responsibility for the direction of their learning, make mistakes, learn from them and iterate, build collaboration skills, develop strategies to overcome obstacles, learn to regulate their emotions, become curious about the world around them, and ask conceptual questions rather than focusing on facts and procedures. This type of learning emphasizes authentic experiences and practical interactions, over traditional teaching methods like lectures and textbooks, and allows learners to develop problem-solving, critical thinking, and collaboration skills applicable in a variety of contexts. In the past, this approach to learning has been commonly used in university labs, industrial workshops, and entrepreneur innovation labs, and more recently in makerspaces (Cevallos et al., 2020; Flanagan-Hall et al., 2018; Land, 2000; Weinmann, 2014).

Makerspaces are open spaces with do-it-yourself (DIY) approaches and occur in co-working spaces, collaborative clubhouses, libraries, community centers, school innovative spaces, and science museums (Lande & Jordan, 2014). They are being adopted as promising learning environments (Tomko et al., 2021) for empowering people to create personally meaningful artifacts while cultivating 21st century skills (Trilling & Fadel, 2009). They contain fabrication tools and resources students can use to bring ideas to life and create physical objects that reflect their creativity and personal expression. In these environments, learners gain knowledge through hands-on problem solving and interacting with peers, physical objects, and equipment. Makerspace activities involve assembly, construction or tinkering with tangible objects; personal expression such as decorating an object; peer socializing; presentations and sharing information with other makers (Lee et al., 2019). Makerspaces have become widely known as places where people engage with constructionist learning principles (Papert, 1980), develop a "maker mindset" (Dougherty, 2011), foster community and develop identity (Blikstein, 2013; Niaros et al., 2017; Peppler et al., 2016), foster innovation and entrepreneurship (Farritor, 2017; Niaros et al., 2017), develop design thinking skills (Blikstein, 2013; Peppler et al., 2016), and strengthen self-efficacy (Andrews et al., 2021).

Despite these affordances for process-oriented and student-centered learning, there are many challenges for teaching and learning in makerspaces. Fabricating physical artifacts is a time-consuming process that often involves interacting with STEM phenomena that are invisible (such as the flow of electricity through wires, or the changing magnetic fields in motors). Although these interactions can provide opportunities for learning, students can become focused on achieving a product rather than gaining deep understanding (Blikstein, 2013; Dougherty, 2011). A founder of the maker movement, Dale Dougherty (Dougherty, 2011), mentions that makers often are just *"playing with technology … They don't necessarily know what they're doing or why they're doing it."* One reason is that students have difficulty visualizing the invisible phenomena they are interacting with, which makes it more difficult to investigate and communicate about these topics (Radu et al., 2022,b; Radu & Schneider, 2019a). Another reason is that designing and creating objects is time consuming, and students tend to focus on using tools for production rather than learning (Blikstein, 2013; Harron & Hughes, 2018). Furthermore, students are interested in a wide variety of self-driven projects, and his can be a challenge for receiving personalized scaffolding and guidance from a limited number of makerspace facilitators or other knowledgeable peers (Blikstein, 2013; Hira et al., 2014; Lock et al., 2018).

These issues can be alleviated when augmented reality is integrated into makerspaces. For example, AR applications could make it easier to see and communicate about invisible phenomena (Radu, Hv, & Schneider, 2021), help in fabrication and debugging tasks (Beheshti et al., 2017), take the role of the facilitator to provide students with personalized scaffolding (Kang et al., 2019), and other opportunities, as will be discussed in the next section.

2.3. Augmented reality for makerspace activities

There is a growing body of research that shows AR applications can be beneficial for enhancing activities that occur in makerspaces, as found through studies conducted in makerspaces and in other environments.

AR applications can help students learn about makerspace-related STEM concepts that are invisible to the naked eye, such as audio waves and electromagnetic fields (Radu & Schneider, 2019a, 2019b), electronic circuits (Beheshti et al., 2017; Restivo et al., 2014; Reyes-Aviles & Aviles-Cruz, 2018), and magnetic forces (Radu et al., 2022,b). These studies find that, compared to traditional instruction, learning with AR typically yields higher knowledge gains, better ability to transfer knowledge to other situations, increased motivation, and deeper student engagement. This data indicates that AR applications have the potential to deepen the learning of invisible STEM concepts in makerspaces. Additionally, research shows that AR can aid broader activities involved in design and engineering. For example, AR applications have been created for helping workers follow a sequence of instructions for disassembly or maintenance of devices (Blattgerste et al., 2017; Tang & Liu, 2021; Wang et al., 2022). AR can also increase collaborative knowledge transfer by allowing a more experienced person to provide instructions, for example between a remote expert and an on-site worker (Aschenbrenner et al., 2018; Mourtzis et al., 2017; Obermair et al., 2020); an instructor and a student learning physics (Radu et al., 2022,b); and an instructor and a student debugging makerspace electronics (Villanueva et al., 2021). Such research shows that AR can produce faster and more accurate task completion, reduced cognitive load, and increased communication grounding in peer collaborations. Other research shows that AR can also aid student understanding of the design process, specifically in the areas of designing, debugging, or presenting ideas. AR can permit designers to create 3D structures prior to construction (Kim et al., 2021; Seichter H., 2003; Wacker et al., 2018, October; Weichel, Lau, Kim, Villar, & Gellersen, 2014, April), or visualize 3D models of structures before they are constructed (Januszka & Moczulski, 2011; Lee et al., 2020; Peng et al., 2018, April; Song, 2020). These studies typically find AR improves the efficiency of the engineering design process by facilitating communication between stakeholders, easing visualization processes, and reducing the time for design and construction. Additionally, AR can enhance the debugging of interactive prototypes, for instance by helping users understand and debug the internal states of robots (Peng et al., 2018, April; Kyjanek et al., 2019; Radu, Hv, & Schneider, 2021) or electronic circuits (Javaheri et al., 2018; Kim et al., 2019; Vanderlee et al., 2020). These studies showed that AR could shorten the time on problem-solving activities when well-integrated into existing workflows. Finally, AR can be used to deliver presentations of design ideas or data visualizations (Bravo & Maier, 2020; Doukianou, Daylamani-Zad, & O'Loingsigh, 2021; Topal & Sener, 2015). These approaches can increase understanding, engagement, and interest over traditional methods.

While these previous studies have found AR can enhance student learning, they are typically not done in the ecological context of makerspaces, and do not provide guidelines for integrating AR in such contexts.

2.4. Augmented reality guidelines

Guidelines are meant to help designers create better educational products. They typically start from formal and informal studies and then become standards (Gabbard & Swan, 2008). In the field of augmented reality, researchers have proposed guidelines for designing applications for various goals such as navigation (Ko et al., 2013), tourism (Kourouthanassis et al., 2013), or learning (Cuendet et al., 2013; Dunleavy, 2014; Laine, 2018; Radu, 2014). These guidelines are specific to the application's intended domain. For example, for learning applications, designers are advised to show the unseen and provide appropriate challenges (Dunleavy, 2014); design for minimalism and awareness (Cuendet et al., 2013); and present relevant information at the appropriate time and place (Radu, 2014).

No guidelines have been created yet for integrating AR into makerspaces, but there exist guidelines about integrating AR into other classroom settings. They discuss topics such as taking into account the time commitment required for learning and using AR applications (da Silva et al., 2016), choosing applications relevant for the curriculum (Pombo & Marques, 2021), encouraging relationships between teachers, students, and other stakeholders (Pombo & Marques, 2021), and considering the flexibility of catering to different classroom activities (Cuendet et al., 2013). More broadly, there are guidelines for integrating technologies into classrooms, such as video materials, online courseware, or new medical devices. This research identifies similar themes such as building relationships between stakeholders (Sandars et al., 2020), accounting for time requirements when working with new technology (Dong & Goh, 2015; Griksaitis et al., 2014), building familiarity with the technology (de Jong et al., 2020; Dong & Goh, 2015; Griksaitis et al., 2014), expecting a fading novelty factor (Griksaitis et al., 2014), and ensuring adequate support staff (Griksaitis et al., 2014).

To date, these guidelines have not specifically addressed the integration of AR into makerspace learning environments. Such guidelines would likely include similar themes, such as supporting familiarity and usability of technology, but also new themes specific to the diverse physical and social environments of makerspaces and how these interact with the capabilities and limitations of AR technology. One method of generating such guidelines is by studying AR technology use with stakeholders in current makerspace settings.

2.5. Co-design as method for exploring design opportunities

The present study uses a co-design methodology, which advocates the early inclusion of stakeholders into the design process, and can help to not only to generate ideas for envisioning future possibilities of AR technology but also empower and engage participants to learn about new technologies, and shape their present and future learning environments (Penuel et al., 2007).

Co-design is defined in various ways depending on the context & the purpose of the research study. Sanders and Stappers (2008) refer to co-design as *"a specific instance of co-creation"*, where *"co-creation"* refers to *"any act of collective creativity"* and *"co-design"* refers to *"the creativity of designers and people not trained in design working together in the design development process"*. Penuel et al. (2007) define co-design in the context of working with classroom teachers as *"a highly-facilitated, team-based process in which teachers, researchers, and developers work together in defined roles to design an educational innovation, realize the design in one or more prototypes, and evaluate each prototype's significance for addressing a concrete educational need"*. Studies evaluate co-design according to different goals. Some focus on evaluating the end products at the end of the process (Alhumaidan, 2017; Cockbill et al., 2019) while others measure participants' experiences, attitudes, and subjective experience of the co-design process (Pallesen, Byberg, & Kristiansen, 2019; Penuel, Roschelle, & Shechtman, 2007; Van Mechelen, Schut, Gielen, & Klapwijk, 2018). The impact of the co-design process on participants is documented in a variety of contexts, and previous research shows it can lead to familiarizing end users with the products being developed and the general subject matter (Cockbill et al., 2019; Cook-Sather & Matthews, 2021; Thabrew et al., 2018); enhancing relationship among stakeholders and helping participants develop insights in others' perspectives (Cook-Sather & Matthews, 2021; Hyett et al., 2020; Van Mechelen, Schut, Gielen, & Klapwijk, 2018); and soliciting positive emotions such as a sense of empowerment and pride in participants' contribution (Cook-Sather & Matthews, 2021; Hyett et al., 2020; Penuel et al., 2007).

Research literature about co-designing AR technology for makerspaces is lacking, but there exist several explorations of co-design with AR technology in other educational domains. Cuendet et al. (2013) present AR projects for classroom orchestration that were co-designed with teachers; the research focused on application features and design guidelines that were generated through that process, rather than discussing the co-design process stages. Buchner and Kerres (2021) engaged students, teachers, researchers, and AR experts collaboratively to design AR-enhanced learning and teaching materials, as part of a workshop aimed at developing knowledge about computer science. Garcia (2020) created an AR history application by engaging teachers, students, and researchers in a co-design process where students were involved in the design of the application, as well as in the evaluation of the final prototype. Pinto et al. (2017) used co-design between teachers and researchers, as a method of exploring how AR can enhance educational board games and leading to the generation of a prototype that was evaluated with children. Alhumaidan et al. (2015) proposed a co-design and research plan for generating AR books with children, through co-design activities between children, teachers, and researchers; these started with brainstorming and low fidelity prototyping, and ended in a high-fidelity prototype that is evaluated in a real classroom, followed by debriefing with students. Alhumaidan (2017) and Alhumaidan et al. (2018) executed this process to generate ideas for AR textbooks and evaluate prototypes.

This previous research has shown that co-design is a valuable method for exploring future applications of technology, and it has specifically been used in generating AR ideas for enhancing classroom orchestration, computer science and history education, educational board games and AR-enhanced textbooks. It is feasible that the co-design method can be used to explore future of AR technology for other domains, such as makerspaces. We expect this approach will yield a variety of AR design opportunities, and that participants will develop a deeper understanding of AR technology while gaining a deeper sense of empowerment and agency in influencing future makerspace environments.

In summary, this literature shows that both augmented reality technology and makerspaces are educationally valuable and are growing in popularity. It is foreseeable that AR applications will be increasingly integrated in makerspaces, since they have the potential to enhance student learning and fabrication activities. However, there is a lack of research exploring the opportunities and guidelines for integrating AR in makerspaces. The present study addresses this by investigating a co-design intervention in a makerspace course and contributing a set of design opportunities for using AR in makerspaces, a set of themes for how students are impacted by the co-design process, and a set of practical guidelines for integration of AR in makerspaces.

3. Materials and methods

In this section we describe the setting, participants, activities, data analysis methods, and the software materials used in the study.

3.1. Participants and setting

This semester-long user study occurred in the context of a makerspace course taught at the department of Education at a university in the northeastern United States. The course lasted 12 weeks and was attended by 18 graduate students who were in the second semester of a one-year Masters in Education degree. 17 students self-identified as female, and one as 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.

Prior to the study all students voluntarily consented to participate in the study, which was approved by the university ethics committee. Seven students participated in the co-design activities, which involved designing and evaluating AR prototypes in collaboration with the research team. All 18 students from the class participated in the evaluation of the AR prototypes, through in-class observations and survey questionnaires. The research team was composed of four persons who had skills in AR software development and/or AR educational research.

In the course, students were taught about the technical skills and pedagogical aspects of makerspaces. The course had been running for several years prior to this study without any augmented reality technology integration. In the course, all students (whether they participated as co-designers in our study or not) completed weekly or bi-weekly homework assignments while working individually or in pairs. When working in pairs, students self-selected their teammates.

For our study, the course was extended to accommodate AR co-design activities. These activities occurred outside of class in connection to six homework assignments. For each of these occurrences, the research team asked for one student team to volunteer for participation in the co-design activities, after students had finished self-selecting their teammates. A total of six prototypes were generated: three prototypes involved single students working with the research team; two prototypes involved teams of two students; and for one prototype no students volunteered so the research team constructed the prototype by themselves, informed by knowledge about what students were studying in class at the time.

3.2. Co-design phases and activities

The co-design process of engaging with each group of students followed the four stages of the Sanders and Stappers (2014) framework, with an additional midpoint phase dedicated to prototype development (Fig. 1). According to the original framework, there are four phases in co-design: pre-design, generative, evaluative, and post-design. During the pre-design phase, the goal is for researchers and co-designers to understand the context for which they will be designing and prepare them for the co-design process. In the generative phase, the goal is identification of future application scenarios, and the production of ideas that can later be designed and developed further. In the evaluation phase, ideas that have been developed into prototypes are assessed, with the goal of measuring effects and identifying possible problems. Finally, in the post-design phase, the goal is further understanding of how stakeholders' experiences are impacted by the products designed. In our process, we introduced a development phase before the evaluative phase, to capture the activities of developing the prototypes (led by the research team). In our study, we performed the following activities during each stage of the co-design process.

Pre-design phase: Prior to meeting with the researchers, students were given pre-activity reading materials about the role of the study, examples of AR educational applications that already exist, and a description of the AR authoring software used for the study. Then, students and researchers met together for a technology familiarization session (lasting about 30–45 min) to discuss what AR technology is and how it works.

Generative phase: Following the technology familiarization session, students continued meeting with the researchers for roughly 1 h. We used techniques of brainstorming use cases and scenarios, through discussion,

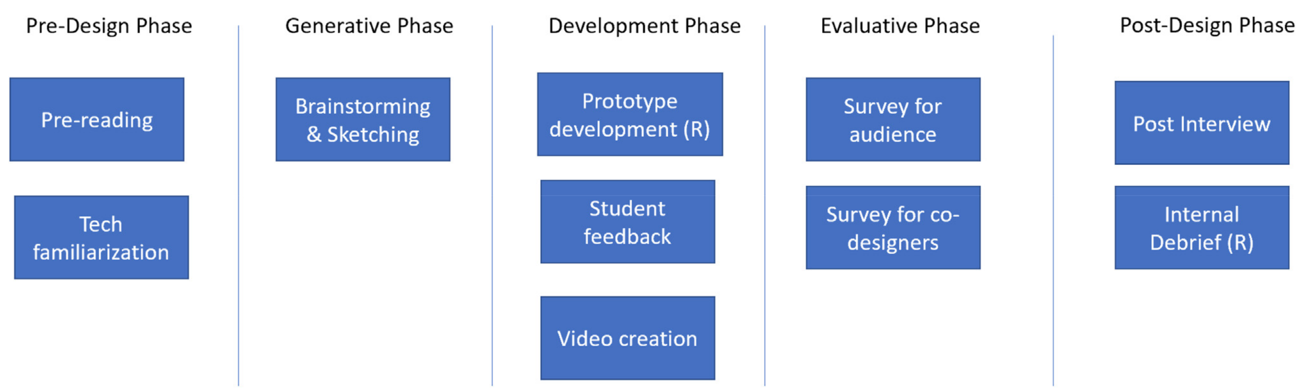

Fig. 1. Activities performed for each prototype according to the phases of the co-design process. R = activity only performed by researchers.

sketching, critiquing, and storyboarding. Students generated ideas of how they envision AR technology could be used in makerspaces, and how AR technology may be used for their specific weekly project. This session was primed through questions such as *"Now that you have seen some of the capabilities of this technology, how do you feel it could be applied to enhancing maker spaces?"* and *"Think of an aspect of this project that is difficult to understand with the naked eye, or that will be difficult to explain to others. How could you enhance it with AR, so that someone else can understand that object more easily?"*. The results of this session were a varied set of ideas of possible uses of AR in makerspaces, and specific ideas for how AR could be used to enhance the students' weekly project.

Development phase: The research team then spent 1–3 days building an AR prototype using the AR software, based on the initial input from students. Then they met with students to gather student feedback and modifications to the prototype. Sometimes students also used the AR authoring environment to discuss and refine the prototype. This prototyping and feedback cycle was iterated multiple times depending on the students' time availability. After the prototype was finalized, a prototype video was generated by the research team in collaboration with the students, with the aim of displaying the video to the other students in the class.

Evaluative phase: The prototype video was then presented in class to all the other students, followed by an in-class survey questionnaire (listed in Appendix A) that gathered feedback from the audience about their reactions to the presented prototype.

Post-design phase: Finally, the research team met with the student authors for a semi-structured interview debriefing session lasting roughly 1 h, in which they were asked their reflections about the designed prototype and co-design process (interview questions are listed in Appendix B). This was followed by an internal debriefing session between all researchers for reflecting on the process.

3.3. Software used to build AR prototypes

For constructing the AR prototypes, we used software developed by current and past members of the research team, available at (HGSE, 2022). This AR software is a middleware for the Unity3D software platform. It permits 3D interactive content to be viewed by multiple users wearing Hololens 2 headsets, and the virtual content can be connected to electronic sensors in the physical world. Creating prototypes requires programming and 3D development, and these were not skills familiar to the student participants; therefore, the software development was done by the research team, with iterative feedback from the student participants. Student co-designers had the opportunity to use the software to view the prototypes and provide feedback, prior to the prototypes being shown to the other students in the class.

The software has multiple features (some features are displayed in Fig. 2). Multiple collaborating users have access to a library of 3D content containing complex simulations (e.g., a virtual simulation of a proximity sensor, placed on the real location of the physical sensor) or simpler static content (e.g., a dinosaur 3D model, or a 2D image of a circuit board). The library is created ahead of time by the software developers, and users can access the library of content to generate, move/resize 3D items. Sensors can be used to detect real world events and influence virtual elements - either in simple ways by connecting the sensor data to an effect on the object (for example, a physical knob's rotation can be detected and used to influence the scale and rotation of a 3D virtual object); or to drive more complex visualizations (e.g. measuring voltage in a circuit and showing it as a virtual graph; or measuring a distance sensor's values can be used to animate a virtual simulation of the inner workings of the sensor; or the position of a 3D object can be tracked and virtual fireworks can be played when the object touches a specific location). Collaboration features allow users to be aware of each other's activities by being able to virtually point to virtual content as well as draw in 3D. They can also use location information features to place arrows pointing to specific objects, or tooltips and text labels to describe spatial locations. Finally, presentation features allow the creation of content that is shown/hidden in a sequence, to allow for creation of step-by-step guided presentations.

3.4. Data analysis methods

Data from various sources were used to answer each of the research questions, as follows:

To answer "RQ1. How can augmented reality be useful for education in makerspaces?" we performed qualitative analysis of data from the generative brainstorming sessions, the prototype development and debrief interviews, and survey data from the evaluative phase. After each **brainstorming sessions** with student co-designers, one researcher (the first author) collected a list of ideas that students mentioned about the use of AR for enhancing makerspaces in general and in specific relation to

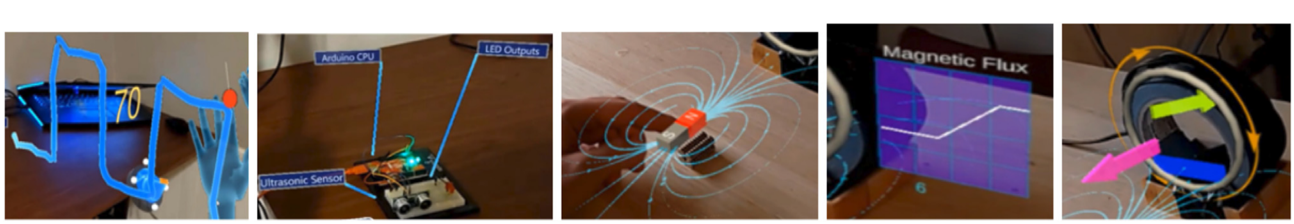

Fig. 2. Features of the AR authoring software (sketching, labeling, 2D overlays, dynamic graphs, and 3D overlays).

Table 1
Timing of prototypes and topics with which they were associated. Brackets indicate how many students participated in the prototype. R = prototype that only involved students in the evaluation phase.

Week	2	3	5	6	10	12
Class topic	Laser cutting	Advanced laser cutting	Child dream toy, 3d printing	Electronics	Programming	Final project
Prototype	Maze (1)	Kerf (1)	Dinosaur (2)	Sensors (R)	Blocks (1)	Marbles (2)

their projects. If participants mentioned other ideas during the prototype development phase or debrief interview phase, these ideas were also added to the initial list. Additionally, an **evaluation survey** was administered in each assignment week to the other students, to collect reactions upon seeing the AR prototype. After each survey, one researcher (the third author) analyzed the survey responses and coded student open-ended answers for other ideas about possible uses of AR. If an idea from one week overlapped with ideas from previous weeks, the same code was used; otherwise, a new code was introduced. At the end of the semester, the codes relating to possible uses of AR from these datasets were merged and grouped (in collaboration between the first and third author), resulting in the themes and sub-themes for opportunities reported in this paper under Section 4.1.2. Quotes from students gathered during debrief interviews and class surveys were also used to illustrate specific impacts of each project more richly, as presented in this paper under Section 4.1.1.

To answer “RQ2. How are students impacted by the process of co-designing AR technology?”, one researcher (the second author) qualitatively analyzed themes in the co-design students’ **debrief interviews**. The interview questions (listed in Appendix B) covered topics such as impact of the co-design process and suggestions for future improvement. After each interview was transcribed, the researcher analyzed the transcript and coded ideas that emerged from student answers to each question. Codes and illustrative quotes were aggregated in a spreadsheet updated each week. If an idea from one week overlapped with ideas from previous weeks, the same code was used; otherwise, a new code was introduced. At the end of the semester, the codes were grouped (in collaboration between the first and second author) into the themes and sub-themes reported in this paper under Section 4.2.

Finally, to answer “RQ3. What are practical considerations for integrating AR in makerspaces?”, we used data from **reflections from all researchers** on all phases of our study, specifically focusing on logistical, pedagogical, and technological challenges encountered during the process; as well as data from student debrief interviews relating to logistical considerations. At the end of the study, all researchers pooled their thoughts about these topics into one document. Additionally, the document was extended to include logistical considerations generated from student interviews (which emerged from the analysis described above for RQ2). Finally, the ideas in the document were grouped (in collaboration between all researchers), resulting in the four categories of guidelines presented in this paper in Section 4.3.

4. Results

In the following sections we first focus on “RQ1. How can augmented reality be useful for education in makerspaces?”. We first describe several prototype experiences built with students, and we present a broader listing of different subject areas where AR can be beneficial. Then we present our findings about “RQ2. How are students impacted by the process of co-designing AR technology?”. Finally, we reflect on the process of integrating AR in makerspaces and provide guidelines to answer the research questions of “RQ3. What are practical considerations for integrating AR in makerspaces?”.

4.1. How can augmented reality be useful for education in makerspaces (RQ1)?

In this section, prior to answering the research question, we first provide detailed information about the prototypes generated during the study and the ideas that emerged during their development. Then, in section 4.1.2 we answer the research question by reflecting on broader themes of how AR can be used in makerspaces. Table 1 shows the topics of the prototypes and their semester timing. Table 2 in Section 4.1.2 summarizes the areas for how AR technology can be useful in makerspaces and which prototypes illustrate each theme.4.1.2

4.1.1. Prototypes and student evaluations

The six prototypes, along with their construction and evaluation, contributed significantly to understanding AR opportunities for makerspaces (RQ1), understanding impacts of co-design process on students (RQ2) and for generating guidelines for integrating AR technology in makerspaces (RQ3). To illustrate the rich data collected through this process, we describe each prototype, along with quotes from the students who were authors of the prototypes and from students in the class who observed the prototype. Emerging themes are shown in bold.

4.1.1.1. Maze prototype. For this project, illustrated in Appendix C video and Figs. 3 and 4, the student author first created a wooden maze in the shape of letters, with a ball moving through it (Fig. 3 left). Augmented reality was used in to enhance the finalized form of the object, and to communicate its creation process and its future uses. One of the challenges in makerspaces is that students engage with the process of creating artifacts, but often the process for creating an object is not easily visible in the finalized form. With AR, the student showed how the maze path was generated by merging rectangular shapes, which were copy-pasted with modification within each letter (Fig. 3 right). AR was also used to add visual special effects to the object once the ball reaches the end (Fig. 4, left), and to provide hints for moving the ball through the maze by displaying arrows (Fig. 4, right).

This project touches on how AR could impact multiple aspects of the makerspace experience. The students in the audience felt an **increased sense of agency** while seeing AR applied to makerspace projects, e.g. *“It was exciting to see a classmate use AR as part of their project. It made me feel like I could do that eventually too.”*. The author of the project also mentioned: *“I didn't think I was able to make something. I didn't think that I could have the skillset to do. But then once I started doing this, I realized I already have much of the skills to do this …. It was empowering to realize I knew more than I thought. And stimulated me to think of new things … and excitement of ‘oh what else can I do?”*. Additionally, when AR was used to

Fig. 3. Left: Final maze object as seen without AR (ball not visible). Right: AR overlay showing how the maze path was created through copy-pasted rectangular shapes.

Fig. 4. Left: Maze with AR visual effects celebrating its completion. Right: Maze with arrows to provide hints to the user.

show the **design process** (Fig. 3 right), students in the audience mentioned that it was helpful: *"I think the part where it showed the overlay of the maze was really helpful to understand the design"*. Seeing **guidance information** (Fig. 4 right) was found to be helpful, for example a student mentioned it was helpful *"having arrows popping out in sequence showing the steps"*. Although students appreciated these facets, the audience also expressed confusion about **making sense of AR representations**, e.g., one student mentioned *"I was confused by what the overlays of the AR meant. I would have appreciated more explanation around that"* and another student mentioned *"Sometimes it is too messy and dizzy. I will say having less representations at the same time might help."*. These confusions hint at the importance of properly structuring AR presentations.

4.1.1.2. Kerf prototype. Sometimes students make discoveries during the process of fabricating shapes, and augmented reality can be useful to educate others about those discoveries. In this project, illustrated in Appendix C video and Figs. 5 and 6, the student author made a physical animal made from laser-cut flat shapes, which contains a cylindrical shape (Fig. 5 left). The cylindrical shape was created by taking a flat piece of wood and cutting a "kerf" pattern (i.e., a series of thin cuts), to make it bendable. During this process, the student discovered through failure that whenever kerf bending is used to turn a flat shape into a circular shape, there is extra length introduced when the piece is bending, which needs to be accounted for in the circumference of any holes where the piece will fit. This was a challenge during the construction process, and the student chose to teach the rest of the class about this issue, through an AR prototype. AR overlays were first used as x-ray to show the shapes that are not easily visible, specifically highlighting the flat shape which contains a circular hole shown in green (Fig. 5 middle). The AR presentation then shows how the initial cylindrical shape had a circular radius larger than the hole (Fig. 5 right). The AR was then used to show how, when starting with a flat shape (Fig. 6 left), bending it introduces small spaces that increase the circumference (Fig. 6 right). The AR animation shows how the original flat panel needed to be shorter than planned, to account for extra space from the bending.

The use of AR in this prototype was to show how objects can be assembled, and issues that can arise when assembly happens. This prototype highlighted the value of augmented reality to **teach about challenges encountered** in the **design process**. Students in the audience mentioned that they *"could understand [the author's] thought process in trying to figure out the measurements of her design"* and *"It was helpful to see how the flat piece of wood was then bent into a cylinder. It helped me visualize how you would go about making a 2D piece of wood into a 3D object using kerf bending"*. The AR also helped students to understand the **assembly process**: *"I loved the visual representation of how the pieces fit together and the inner/outer circumference"* and *"being able to see how the object was folded and fit (or failed to fit) into the whole"*. Finally, as in other prototypes the audience students **felt engaged** by being able to learn through AR, mentioned that *"It makes the learning more interesting"* or *"If everybody is able to use AR machines in class, it would be much more engaging."*.

4.1.1.3. Dinosaur prototype. The process of creating physical artifacts requires lots of time, especially in the case of waiting for 3D printed

Fig. 5. Left: animal shape created from flat wooden pieces, including a piece curved into a cylinder. Middle: The internal space where the cylinder rests. Right: The initial cylinder that was too large.

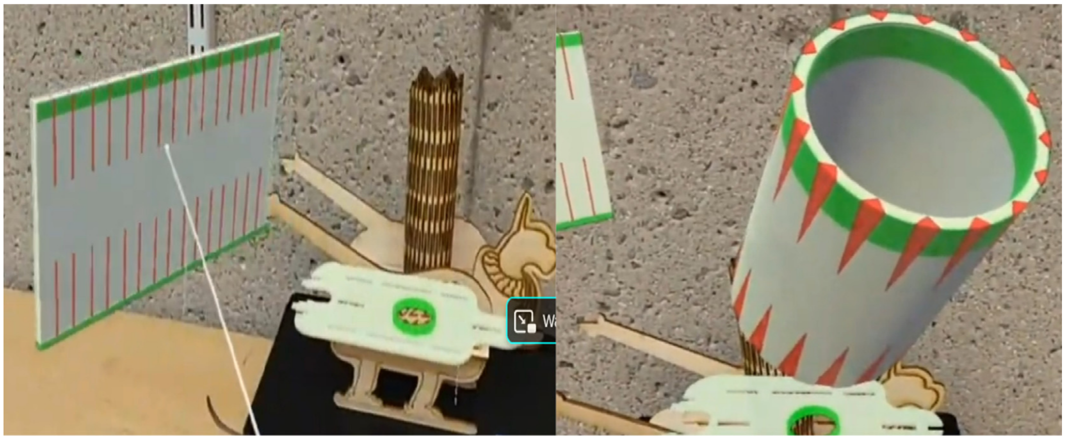

Fig. 6. Left: The flat piece that was curved into the cylinder. Right: The spaces (red) introduced in the outer circumference when the piece is curved. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

shapes, and the designer may not fully understand how a shape would feel until it is fully constructed. In this project, illustrated in Appendix C video and Fig. 7, AR was used to visualize the end product prior to building it. Students used AR to visualize and discuss various ideas of a toy. The students were planning to construct a dinosaur as an educational gift for a child but were not sure specifically how it would feel to manipulate it. A first AR prototype was used to illustrate the idea where the toy could provide a dinosaur body where various types of tails or legs or heads could be attached (Fig. 7 left). While the student interacted with the prototype, they decided that the idea was not very educational for the child and decided to change it: the dinosaur would be created from a transparent body and opened in half, and inside the dinosaur would be another piece representing the dinosaur bones. The AR prototype was updated to reflect this (Fig. 7 right). Students discussed this option together, to understand how it would feel, and whether it was worth building it using 3D printing materials.

This prototype touches on several areas of how makerspaces can be enhanced by AR. The project showed how **the design process** can be enhanced, by visualizing ideas understanding constraints and alternatives, and allowing quick iteration. This let students visualize the scale of the object and understand how much 3D printing material would be required, which caused them to change their project idea to not involve 3D printing. Additionally, the AR simulated how the **assembly** of the object would occur, and how a user would interact with it. The students felt this process *"saved a lot of materials and time because I could see it in the AR version first"* and *"[We] probably would've stuck to one idea and failed much later. Might not have known what could be done/not done and might not have seen what things would need adjustments"*. For this project, augmented reality also helped students **collaborate** and **present their work** to others. The students mentioned that *"Using AR adds a layer to help us work through the design process"*, and that AR could be specifically useful for improving collaboration and presentation, by manipulating things together while brainstorming, aid conceptualization of own project ideas, and help brainstorming. The audience members watching the AR video presentation also felt that seeing this process in AR was useful to *"explain the challenge of forming objects",* and to *"imagine the final product",* and to *"understand how pieces fit together"*, possibly increasing the sense of community participation.

4.1.1.4. Sensors prototype. Electronics sensors are used to detect events in the real world (e.g., a button being pushed), and to use that information to influence something (e.g., turn on a light). Sensors are typically physical objects whose internal electric behaviors change in response to the external events, but their internal functions cannot be easily seen. For this project, illustrated in Appendix C video and Fig. 8, AR visualizations were created to show how three different electronic sensors work internally (Fig. 8 left). A push button sensor detects if a button is pushed or not; AR was used to illustrate its internal behavior (Fig. 8 middle), showing how the flow of electricity through the wire is activated when the button is pushed, as well as showing a graph illustrating the strength of electric signal as the button is pushed. A distance sensor detects when an object is close or far; AR was used to illustrate how it works (Fig. 8 right), by having an infrared light source that shines invisible light on nearby objects, and a sensor that measures the intensity of light reflected back from those objects. Finally, a light sensor detects the amount of ambient light. AR was used to show how this sensor restricts electricity

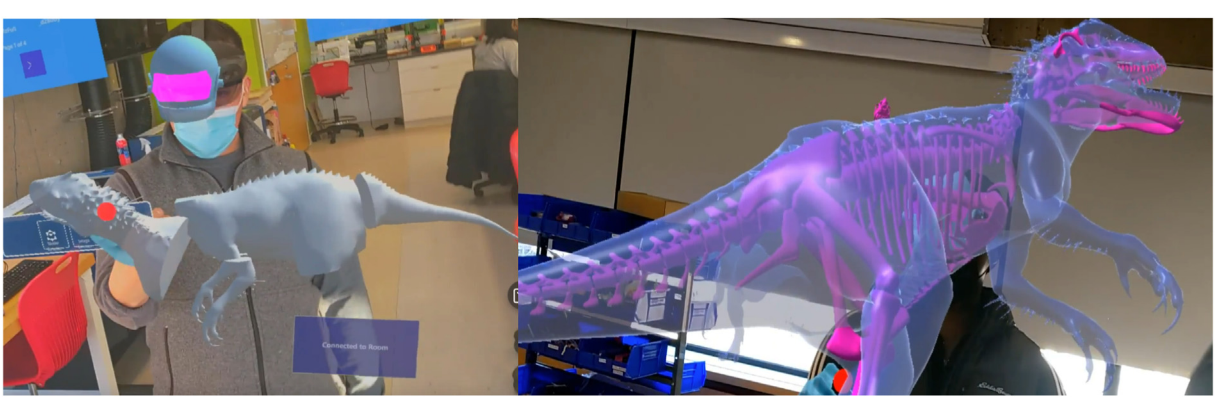

Fig. 7. Left: first prototype where the dinosaur has multiple connectible body parts. Right: second prototype where two students manipulate the dinosaur as it contains a transparent half shell and an internal skeleton.

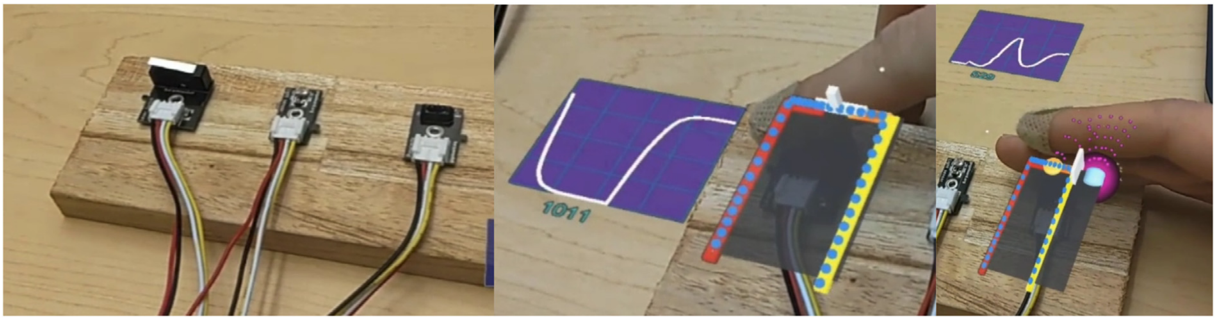

Fig. 8. Left: three sensors (button, light, proximity). Middle: AR overlays on the button sensor showing signal strength and flow of electricity. Right: AR overlays on the proximity sensor showing signal strength, infrared light source, and detector.

depending on the amount of light shining on it (not shown in Fig. 8).

For this prototype, the students felt the AR was helpful to **see hidden or invisible phenomena**, specifically that AR was helpful in *"visualizing the circuitry parts that are either too small to see or invisible"* or *"visualize the electricity"* and *"showing invisible flow"*. Furthermore, students felt it helped them to gain a **deeper understanding** of how electronic sensors work: *"I think understanding the inner working helped me understand the sensors better"*, specifically helped by interactivity: *"It was really nice being able to see the visualizations in real time of how the switches actually work!"*

4.1.1.5. Blocks prototype. Digital programs are difficult to debug because their execution is invisible to the naked eye. This project, illustrated in Appendix C video and Fig. 9, involved programming a game in which the user moves two cubes, and a fireworks effect is generated when two cubes are properly stacked on top of each other. The program used to trigger these effects requires monitoring the relative X/Y/Z positions of the two cubes, such that the firework is only triggered when the cubes are appropriately stacked. The student wanted to use AR to visualize how different parts of the program were triggered as the user manipulates the two blocks. This way, the AR functions as a way of understanding the program and debugging its behavior in real time.

When students observed programming through this AR medium, they felt the AR helped them **understand the program** better, mentioning it was useful to *"[be] Visualizing the code and working principles of the project"* and that *"I thought it conceptualized what can be a very technical and difficult to learn aspect of coding really well!"*. This also applied to the student author, who felt that the process of designing the AR experience helped her understand the code more easily. It also appeared to **increase student engagement** and interest in programming: *"It is cool to watch the algorithm behind"* and *"They are more fun to watch because of the AR"*.

4.1.1.6. Marbles prototype. Augmented reality can also be used to display instructions and guidance for users that are unfamiliar with an object. For this project, illustrated in Appendix C video and Fig. 10, students built a physical representation of a circuit, whereby flowing marbles represented electricity moving through different components such as resistors and motors (Fig. 10 left). Augmented reality was used to inform novice users about what the different components represented (Fig. 10 middle), and to guide users through what was occurring in different parts of the object (e.g., noticing how the flow of marbles slowed down at specific points in response to user actions; Fig. 10 right). This AR guidance served to familiarize the user with the object and better scaffold the learning experience.

This project showed how AR can be useful in introducing a project to an audience, and to guide the audience's attention. For example, the authors of the project mentioned that the AR helped **introduce the project and communicate its functions**: *"[The AR] helped us present/introduce our project to other people … AR was useful for explaining different parts of the project"*. Students in the audience mentioned things such as *"I think that the most valuable thing about the AR presentation today is it helped me understand the purpose of the toy set as well as its components. For example, without the AR presentation, I wouldn't have known the little white thing was a fan"*. The AR was also helpful to **direct and guide learner attention** to specific parts of the object, reducing the need for other documentation or instructor - for example one student said, *"I thought the text explanations were helpful to understand what I should be paying attention to in the demonstration."*. The authors mentioned *"[the AR] can guide the students to pay attention to specific things and understand what the toy is doing/what relationships are happening in the toy. The AR helped to direct/instruct the user as they played long term; so, it can replace an actual human instructor"*.

4.1.2. General areas of AR opportunities in makerspaces

The creation of prototypes served to illustrate several AR opportunities and to gather student feedback about their potential impact. To understand which other opportunities exist for AR to enhance makerspaces, we aggregated themes from the evaluative phase of our co-design process, along with themes from the generative phase of brainstorming ideas with students. In this section, we describe the different categories of opportunities for how AR can enhance future makerspaces (summarized in Table 2) and illustrate these with examples from discussions with students.

Facilitating Object Assembly/Disassembly: This theme emerged in the Kerf and Dinosaur prototypes, as well as in brainstorming sessions. Augmented reality was found to be useful for showing how an object can be taken apart (e.g., showing the student the step-by-step instructions while they are deconstructing it), or showing instructions for how an object can fit together from different pieces of a construction kit. The Kerf prototype worked especially well for this purpose, especially since the construction process had the added complexity of turning 2D shapes into 3D structures through bending and connection. Beyond actively guiding the user, students also thought AR was valuable as a passive tool, for example for recording how a student deconstructs an object and allowing them to replay the recording backwards while manipulating the object, to guide reconstruction.

Enhancing the Design Process: This theme emerged in the Maze, Kerf, and Dinosaur prototypes, as well as in brainstorming sessions.

Table 2
The areas of opportunities for how AR can be useful in makerspaces and the prototypes that illustrated those opportunities (described in Section 4.1.1).

Areas of opportunities for AR	Prototype(s) reflecting this topic
Facilitating Object Assembly/Disassembly	Kerf, Dinosaur
Enhancing the Design Process	Kerf, Dinosaur, Maze
Learning Scientific Concepts	Sensors, Blocks
Debugging Existing Objects	Sensors, Blocks
Adding Object-Based Entertainment	Maze, Blocks
Contextualizing	Marbles
Orientation and Training	Maze, Marbles
Community and Inclusion	Dinosaur
Presenting and Teaching	(all)

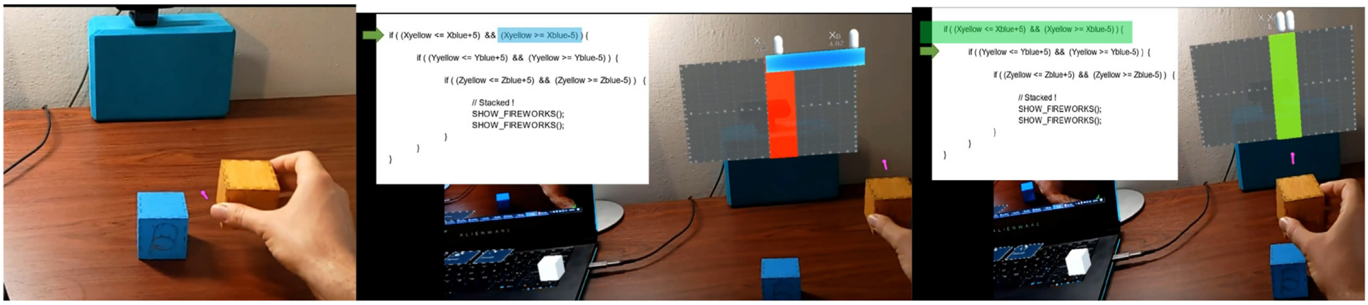

Fig. 9. Left: The AR prototype activates an effect when the two blocks are properly stacked on each other. Middle: The AR shows how only a part of the program is activated when one block is too far from the other in the X dimension. Right: The AR shows how the program progresses when the blocks are aligned in the X dimension.

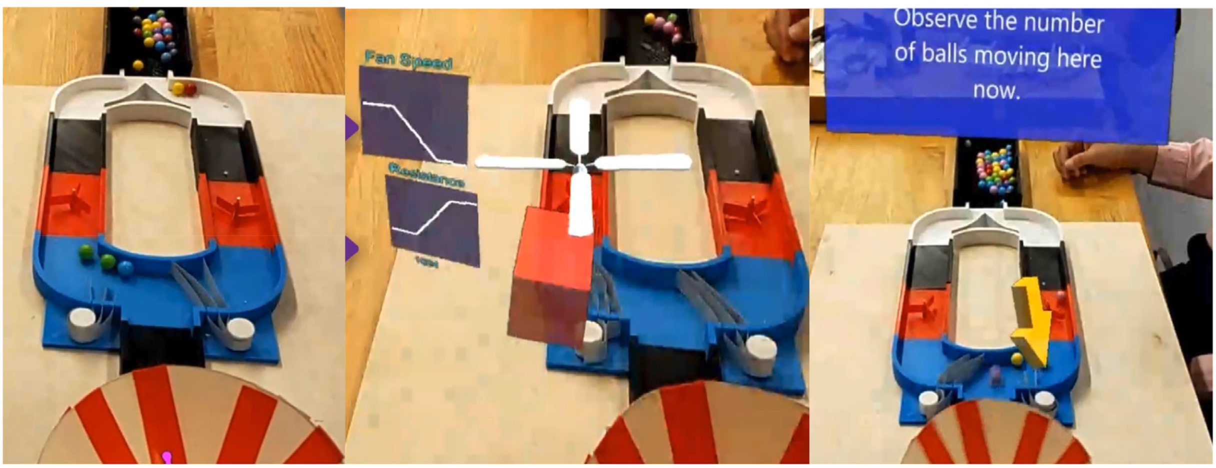

Fig. 10. Left: The toy representing an electric circuit. Middle: AR overlays showing what the physical areas represent (i.e., a turbine, and a resistance zone). Right: AR overlays guiding user attention during toy usage.

Students felt that AR can enhance the larger process of designing objects. Specifically, AR could speed up the design process by helping students envision future iterations before physically building the objects (as illustrated in the Dinosaur prototype, where AR helped students envision and manipulate objects before building them, helping students to iterate faster and avoid spending time constructing objects that would not be desired). AR can also be used not just to visualize the object, but also how it may function in its intended environment (for example, while building a physical steering wheel, AR can be used to visualize how the car environment would look around the steering wheel). AR can also be used to make quick modifications to objects, for example envisioning how objects would look if they were made of different colors; or when real materials are not available to construct something, AR can overlay virtual components on real objects (for example showing how a robot arm would look if covered by skin) to illustrate how a final object would look prior to spending time constructing or waiting for the materials. This process is valuable when done collaboratively with input from team members and stakeholders, and AR could help collaborators engage in an iterative design process by allowing multiple users to communicate with each other about their vision for their projects, such as in the case of the Dinosaur prototype, and potentially also allowing them to manipulate these visions and collect feedback from other users, prior to building any physical objects. Finally, students also thought that AR could be used to create a better bridge between the physical world and the computer-generated content that is required to build physical objects. For example, being able to see how a 3D model would look in the real world before 3D printing it or being able to see how 2D laser cut shapes would look once assembled into a 3D structure - and allowing quick modifications, for example modifying 2D laser cutter drawings and visualizing how they would look in 3D shape prior to laser cutting.

Learning Scientific Concepts: This theme emerged in the Sensors and Blocks prototypes, as well as in brainstorming sessions. Students thought AR would be valuable for learning about specific concepts that often come up in makerspace projects. Invisible phenomena occur on different topics in makerspaces and could be helpful for AR applications: for example commonly explored topics such as electronics (e.g., using AR to show internal workings of circuits as one manipulates them, as illustrated by the Sensors prototype), robotics (e.g., showing how programs relate to the real world, or the current state of sensors perceived by a robot), and physics (e.g., using AR to show the internal forces present on a structure as it is manipulated); and more distant topics such as geometry (e.g., illustrating how repeating shapes are used to generate objects of different shapes), ecosystems (e.g., visualizing behind the walls of the makerspace to understand how it is integrated in the rest of the building), psychology (e.g., using visualizations on a maze to illustrate how the human brain may approach solving it), chemistry (e.g., showing the internal chemistry used in laser cutters or 3D printers), etc. Furthermore, AR can also be used to illustrate more abstract topics such as computational thinking (e.g., using AR to show how the pattern of input-output computation appears in different parts of a makerspace, from sensors that drive robots, to sensors that control the laser cutter), or understanding complex systems (e.g., how small changes in a robot's construction led to different movement patterns).

Debugging Existing Objects: This theme emerged in relation to the Sensors and Blocks prototypes, as well as in brainstorming sessions. When AR applications are present to teach students about specific things, such as circuits or programs, it is possible for students to use them for interactively understanding and debugging objects while constructing them. For example, the Blocks prototype was useful to understand how a program behaves in relation to physical actions, and students could use it while building other programs with similar behaviors. As another example, if students use specific sensors, they could use the Sensor visualization prototype to better understand why their own sensor does not work. Similarly, if tools exist for measuring circuits or visualizing working programs, students can use these in real time to debug their creations. It is worth noting that, for students to be able to debug using AR tools, these kinds of AR tools need to be designed to support a wide range of use cases (e.g., an AR tool for visualizing energy inside circuits will have more success if it can be applied to many kinds of circuits).

Adding Object-Based Entertainment: This theme emerged in the Maze and Blocks prototypes, as well as in brainstorming sessions. AR can be used for enhancing the entertainment value of objects. For example, in the Maze prototype, AR was used to provide special effects to the object when the user solved the maze. Other similar ideas included using AR to add virtual characters or other virtual objects to projects, to provide challenge or narrative as users engage with the objects.

Contextualizing: This theme emerged in the Marbles prototypes, as well as in brainstorming sessions. Students thought it would be possible to use AR for contextualizing an object to understand the larger context where it would fit. For example, if a student is constructing a motor, AR could be used to understand how it would fit into a larger object such as a car or a windmill. Or if the student builds a toy dinosaur, AR could be used to envision the larger environment where that dinosaur would be living had it been alive. AR was also thought to be valuable for envisioning what an environment would look like if the students were in a real work environment, for example if they were operating their robot in a real industrial warehouse.

Orientation and Training: This theme emerged in the Maze and Marbles prototypes, as well as in brainstorming sessions. AR technology can be used to learn about objects in the makerspace environment. AR can be used for general orientation (e.g., using AR visualizations to show what are the different areas of the makerspace and what kinds of activities might be done in them) as well as for familiarization with specific tools (e.g., using virtual visualizations to provide information about each machine or tool). AR can also be used to guide and train people how to use machinery (e.g., providing step by step instructions for using or maintaining the machinery), how objects or machinery works (e.g., such as in the Marbles prototype where AR was used to guide a user in understanding and using the object; or AR can be used to visualize air flow around the laser cutter; or to illustrate what happens internally in the laser cutter when the lid is lifted), and how to do things without risk (e.g., showing the range of motion of a CNC machine; or showing the acceptable level of flame in a laser cutter).

Community and Inclusion: This theme emerged in the Dinosaur prototype and in brainstorming sessions. AR was thought to be valuable for improving a makerspace sense of community between the physical users of the makerspace, and increasing inclusion to other students or instructors who cannot be present. AR can be used to allow remote collaboration, for example from users who are at home or in a different makerspace and connected in an embodied way through VR or 3D scanning methods (Radu, Joy, & Schneider, 2021). Connections between students in the same makerspace could be enhanced by AR, as the technology can allow students to see 3D visualizations of past or present student projects, either if students are present (such as in the Dinosaur prototype where different users could look at student designs) or even if students are not physically present, to learn what others have created or get inspirations from other people's creations.

Presenting and Teaching: Students frequently discussed using AR as a valuable tool for teaching or presenting content to other people. We discuss this as a separate category here, although we acknowledge that the activities of presenting and teaching can be used with AR applications in any of the other categories listed above. This category emerged in the Marbles and Dinosaur prototypes and in brainstorming sessions. Specifically, students discussed wanting to use AR to teach about one's own project (for example, to show how the invisible phenomena inside the project; or to show inside the object without disassembling it; or to teach the design process of how the object was created). Additionally, AR presentations could also be used to gather feedback from other students (for example, students could leave virtual notes or virtual drawings on one's own project, while discussing with the project author or even while the author is not present).

4.2. How are students impacted by the process of co-designing AR technology (RQ2)?

The process of co-designing with students generated many possible uses of AR, and it is expected that in the future, teachers and technology designers will continue to involve students in co-design. In our study, we observed the following impacts on student co-designers:

Increased Sense of Engagement: Generally, a strong sense of engagement is positively associated with increased involvement, increased proactive behaviors, and increased willingness to overcome challenges that may occur in the process of doing activities. All the students expressed feeling happy with both the process and results of the co-design, gaining an increased interest in technology and makerspace in general. Participants often expressed positive engagement such as *"the brainstorming and figuring out the design sequence were enjoyable for me";* and *"[I am] definitely very happy about this!"*. Such results indicate that facilitators of the co-design should make sure the experience is enjoyable and positive for all participants to optimize participants' proactive involvement in the process.

Increased Sense of Empowerment and Familiarity with Technology: Familiarity with the technology means that participants become more knowledgeable about what the technology is and how it may be useful under certain contexts. Increased familiarity is closely related to gaining a sense of empowerment - as participants become more familiar with the subject matter, they in turn become more confident and feel that they can contribute to the development process and the end product, reinforcing a positive impression on the co-design experiences. All participants reported gaining more knowledge and familiarity about the AR, which in terms has made them more comfortable and confident in talking about relevant topics. Seeing the project come into shape also gave the students a sense of empowerment and sense of belonging, that is, feeling that they have *"contributed something to the class"*, specifically mentioning *" … I used AR to show how it can be made, and it gave confidence."*; *"I will have more context if a similar conversion came up in the future"; "seeing the product in the end made me very proud … knowing I played a part in designing it …"*. This shows that co-design is a suitable method to introduce familiarity with certain technologies into existing courses.

Engagement with Design: Co-design provides the participants an experiential opportunity to engage with design, which includes common design activities such as brainstorming, prototyping, communicating ideas with design partners, and such an experience helps participants gain design knowledge. Since the participants in our study are students pursuing a master's in education, many of them have been previous teachers and many value the design of curricula and learning experiences. Five of the seven participants have reported themselves benefiting from co-design in improving their educational design knowledge. For instance, participants mentioned that *"co-design reminded me of the importance of working with others"* and *"(co-design) taught me about the value of prototyping early"*. One participant mentioned that co-design reminded her of the importance of *"having lots of ideas and not being attached to certain ones"*. Finally, this process seems to stimulate educators to think of classroom design - for instance, one participant who was a former teacher mentioned that *"being involved in it and using it was very eye opening for me, made me think how can I use it in the classroom, how can it enhance curriculum"*. When the objective is to engage students in design activities, introducing co-design can be beneficial in further facilitating the construction of design knowledge for the students.

Improved Critical Thinking about Technology Design: The co-design process can help stimulate participants think more deeply about how AR can be applied to their projects and in education, which can deepen the participants' understanding and evaluative judgements beyond the co-design sessions. In our study, all participants praised the co-design process as deepening their critical understanding of AR. Participants said things such as *"If we talk to other educators and other designers, we just keep talking about it, because we don't need to create it. But here, because we need to create it and code it, we need to think about what AR can and cannot do more realistically."* and *"It has inspired me to think more about what else AR can do, how can AR be used for education … I still think about it now"*. Some participants also reported that co-design helped change their initial opinions about AR, for example changing skepticism: *"honestly, I used to be skeptical about AR, but now I can see how it can be super helpful for teaching"*; or thinking about security and privacy: *"Having had this experience with AR helped me think about data security in using VR/AR technology"*; or being more critical about designing with novelty effects *"[This process] made me think about not getting enamored by 'fluff' or things that are shiny or will get boring. How can the design be useful in long term, rather than just short term?"*. This indicates that some participants are now taking a more critical stance on the technology's implementation than before the co-design process.

4.3. What are practical considerations for integrating AR in makerspaces (RQ3)?

In the following section we offer themes that teachers and makerspace facilitators can consider when using augmented reality technology in makerspaces. We present considerations into the broader themes of familiarizing students with AR technology, using AR software/hardware, presenting projects with AR technology, and co-designing AR with students. The considerations are summarized in Table 3 and detailed below.

When co-design is used in a makerspace, these guidelines are applicable to distinct phases as indicated in Fig. 11. During the early phases of pre-design and generative activities, considerations must be taken as participants become familiar with AR technology and engage in exposure to AR software and hardware. During the prototype development phase, developers may create the prototypes, but there are considerations for participants as they use the AR software/hardware with prototypes, as well as work on creating presentations with the AR technology. In the evaluation phase, considerations apply as participants and the audience will observe and possibly use the AR prototypes, possibly in the context of demonstrations or presentations. Finally, there are generic co-design considerations that are applicable throughout the co-design process.

Table 3
Guidelines for integrating AR into makerspace environments.

GUIDELINES FOR FAMILIARIZING STUDENTS TO AR TECHNOLOGY
Budget for training time
Understand students' previous experience with AR/VR
Give an interactive introduction
Use examples from class
GUIDELINES FOR USING AR SOFTWARE/HARDWARE
Have technical support personnel
Be mindful of hardware device use
Be mindful of the dynamic nature of physical and social environments
Consider group use
GUIDELINES FOR PRESENTING WITH AR TECHNOLOGY
Be mindful of the role of AR in presentations
Introduce the broader context
Be clear about what is real and what is virtual
Use live demos rather than videos
Encourage social media
GUIDELINES FOR CO-DESIGNING AR WITH STUDENTS
Provide clear communication of goals, roles, and expectations
Situate the participants in context
Consider the tension between class requirements and AR/co-design workload
Consider time constraints
Create a supportive environment

Regardless of whether co-design is being used, teachers can integrate AR into makerspaces in various ways (illustrated in Table 4). AR applications may be used for specific activities (e.g., using AR to help students debug circuits, or to envision 3D designs), or for more open-ended creative activities (e.g., making AR-based presentations, or creating AR prototypes). The guidelines for integrating AR in makerspaces can be organized according to the Active-Constructive-Interactive learning framework presented in (Chi, 2009), which describes different levels of student engagement. This framework defines "active" activities of physically interacting and manipulating learning materials, which can be less demanding than "constructive" activities of knowledge generation through reflection, organization, and presentations, which are in turn less demanding than "interactive" student engagement through discussions and joint co-creative collaborations. As teachers integrate AR technology into makerspace activities, this framework can be used to understand which of the AR integration guidelines are related to supporting different levels of student engagement. Simple "active" engagement with AR technology requires a degree of familiarity and understanding how to use the AR software/hardware; "constructive" activities such as generating AR presentations requires familiarity and understanding of AR technology, as well as knowledge of how to present with AR software; and finally, to engage in "interactive" creative collaborations requires considerations for familiarity with technology, understanding usability of software/hardware, and may involve presenting and co-designing with technology.

In the remainder of this section, we provide more details about each guideline.

4.3.1. Guidelines for familiarizing students to AR technology

Regardless of the level of student engagement, students must be familiar with the technology they will be using, and these guidelines aim to support that.

Budget for training time: Considerable time investment is required when a student learns about a new technology, and especially if students will later engage in creating content using that technology. In our study, more time was needed than anticipated for participants to gain familiarity with the AR technology, especially for those with no prior exposure. It is helpful to allow multiple hours of student activity, for participants to be exposed to technology, and to clarify how the new technology works and what is possible with it.

Understand students' previous experience with AR/VR: There is a wide variety of possible student exposure: some students may never have been exposed to AR technology; other students may have been exposed to VR experiences but do not understand how this differs from AR; and other students may have been developers of AR. Before engaging students with AR technology, it is helpful to get a sense of the class's previous experience and comfort levels. In our study we achieved this by providing students with a pre-activity questionnaire, and clarification questions during our 1-on-1 interactions with students.

Give an interactive introduction: It is useful to expose students early to in-person live AR examples and use-cases of AR applications, before talking about how AR can be used in general for education. This is because often students may think they understand what AR technology entails, but they have misconceptions or are thinking of related technologies like VR. To achieve a clear introduction, the facilitators can walk students through examples of applications (through live demos or videos or student-downloadable apps), so students can gain a more concrete idea about how AR could be integrated into real-life contexts, before they start using or generating their own ideas.

Use examples from class: When teaching students to get hands-on training with AR software, the facilitators should use concrete examples relevant to the class. For example, it is helpful if facilitators can give examples of how AR might improve understanding of 3D printed objects

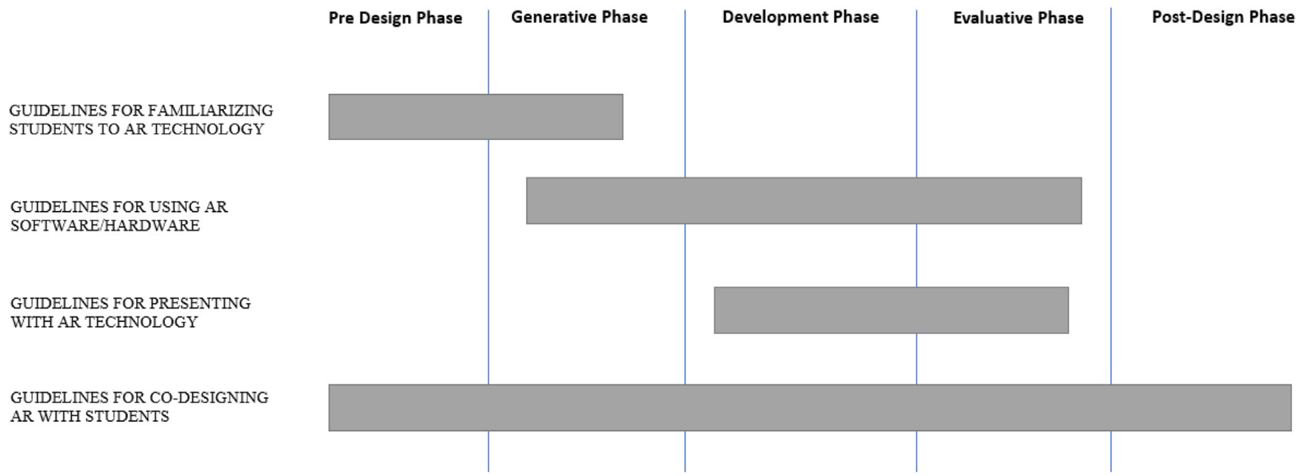

Fig. 11. Applicability of guidelines to different stages of co-design.

Table 4
Guideline themes that apply to supporting various levels of student engagement.

Guideline Themes	Active/ Manipulative	Constructive/ Generative	Interactive/Co-Creative
Familiarity with AR technology	X	X	X
Using AR software/ hardware	X	X	X
Presenting with AR technology		X	X
Co-Designing AR			X

or inner workings of laser cutters. Doing so helps situate the learners in context use and provides motivation and relevance.

4.3.2. Guidelines for working with AR software/hardware

It is important to ensure students have access to hardware, access to technical support, and understanding of the technical affordances and limitations of the technology.

Have technical support personnel: AR applications have technical requirements that a teacher may not be qualified to solve (for example if having internet access is important, the AR devices may need registering on the school network; or usernames/passwords may need to be configured; etc.). It is useful to have someone who is knowledgeable about the software and provides IT support. In our case, we had AR technical experts as the main facilitators to work with the students and provide support throughout the design process.

Be mindful of device use: AR devices can use a lot of battery power when operating (for example our Hololens 2 devices run out of battery after 1–2 h of constant use, and they can overheat in a hot environment). Furthermore, AR devices are fragile and need to be used with care, especially in physically active environments such as makerspaces. In our case, prior to giving devices to students we informed them of the device weaknesses and high costs, and we ensured that devices were kept away from work areas and were recharging when not in use.

Be mindful of the dynamic nature of physical and social environments: AR applications are designed to function in specific contexts of use. For example, an AR application that helps guide the user on object assembly will be designed for specific types of objects and specific kinds of manipulations; thus, makerspace users may need to adapt their objects and activities to fit the limitations of the AR application. Furthermore, AR applications will have specific environmental constraints such as requiring proper lighting or requiring objects to be placed on clear background surfaces, so that AR object detection can work, or requiring specific devices with specific cameras. Finally, the capabilities of AR apps also limit the kinds of social interactions that can occur; for instance, some social AR apps may require all collaborators to be present prior to using the app and may not allow users to enter/exit the application during use. The facilitators and users can become aware of the limitations of software and hardware through proper instructions and experimentation in different environments of use.

Consider group use: When students work together, they can teach each other, problem solve together, and stimulate each other to explore the learning activity. The facilitators may support students working in pairs or larger groups so that they may rely on each other for different perspectives and support. However, the group size will be limited by the types of activities and the size of collaboration supported by the AR application.

4.3.3. Guidelines for making AR project presentations

Students may wish to explain or present their work to other students, with the help of AR applications. When doing so, it is important to take several guidelines into account:

Be mindful of the role of AR in presentations: Presentations can involve augmented reality visualizations for a variety of purposes. AR can be used as a way of explaining something about the student project - for example to help communicate about concepts that are invisible or difficult to explain, such as magnetic fields involved in a student project. Or, AR may be an integral part of the student project - for example, being used to add special visual effects to enhance student engagement with the project. Or, AR may have been used only during a small part of the project's creation, for example to help the student debug the electronic components. When students generate presentations to explain how AR relates to their project, it is important to contextualize the purpose of AR and its role in the rest of the project.

Introduce the broader context: The authors should provide the audience with a clear introduction of the project and its purpose, before showing the AR visualizations. Especially when working with AR technology, students may be excited to show off the use of AR, but it is important to focus presentation time on the non-AR aspects of the project.

Be clear about what is real and what is virtual: When preparing the presentation with AR, the presenters should consider different aspects of how AR visuals may confuse the audience (e.g., Limit the number of visuals that appear at the same time; Do not overwhelm the visual field; Ensure that AR visualizations remain lined up with their corresponding real-world anchors; etc.). Furthermore, the presenter should make sure to explain what is physical and virtual, because it is sometimes difficult for audience members to distinguish between the two. Finally, presenters should follow principles of presentation design (e.g., Combine the narrative with the AR visuals; Explain what is being visualized; Direct audience attention to important pieces; etc.).

Use live demos rather than videos: In our study we found that it is better to show the audience a live demo of the AR rather than video recording, because it creates a more engaging feeling, the audience is more forgiving of misalignments between AR visuals and the real world, and the presenter can adapt their presentation based on audience reactions. If one does choose to show video recording instead, the audio narration needs to be practiced and tailored for the timing of the video.

Encourage social media: Instructors may consider allowing students to present their AR-integrated projects on multimedia or social media platforms (i.e., digital portfolios, Instagram, etc.) to encourage student engagement and participation of the larger community.

4.3.4. *Guidelines for (co-)designing AR with students*

Special consideration is needed when students become creators of AR applications and prototypes.

Provide clear communication of goals, roles, and expectations: It is important to clarify the overall goal of the process, and specifically each participant's role and responsibility. For example, in our process, we wanted participants to generate ideas, not simply confirm and validate ideas from the research team, and specifically we wanted to generate ideas where AR was used as a presentation tool to educate the audience, not simply to enhance learner motivation. This clarifying about roles and expectations ensures open communication and facilitates better collaboration among participants and facilitators.

Situate the participants in context: It is helpful to allocate sufficient time for participants to get familiar with the technology and with the AR headsets and software that they would be using, before engaging in idea generation. It is also helpful to use real-life examples of AR applications to guide the participants and have them relate to their own projects, as a bootstrap exercise to catalyze the brainstorming.

Consider the tension between class requirements and AR/co-design workload: When introducing AR into existing traditional courses, it is important to understand the differences in workload for co-design participants vs non-co-design participants, and possibly adapt the requirements so students who do engage in co-design do not feel unfairly burdened. One approach is to introduce co-design as a voluntary activity, and to provide extra support for the students participating (e.g., extra office hours with instructors). Another approach is to treat AR co-design activities as an integral part of the class rather than extra work added on top of pre-fixed class modules - for instance, the instructor may have different criteria for judging students' assignments for those who engage with AR.

Consider time constraints: When co-designing with students, the overall process needs sufficient time for familiarization, brainstorming, and iterative design. In our process we found that, after students brainstormed AR ideas, at least two iterations were needed for students to view AR prototypes and offer feedback to the developers, prior to final presentation to class. We made sure to communicate this commitment prior to students enlisting in our activities, and the participants expressed their appreciation for how time constraints were noted beforehand so they could set realistic expectations for their experience.

Create a supportive environment: Since co-design may involve multiple parties (e.g., researchers, facilitators, class instructors, students), it is important to ensure an open-minded and mutually respectful environment where people of diverse backgrounds and perspectives feel supported. We found that within technology design discussions, an open mind and supportive environment is especially needed when stakeholders may offer ideas that are not feasible to implement with current technology, or when other technologies may be better suited to achieve similar results. Furthermore, the facilitators should be accessible and resourceful for providing support and feedback even outside of the duration of the co-design activities.

5. Discussion

5.1. *Design opportunities for augmented reality in makerspaces*

The current study identified multiple opportunities for integrating AR into future makerspaces. Specifically, there are opportunities for AR applications to enhance: learning of STEM topics, design, debugging, object assembly/disassembly, contextualization, object-based entertainment, training, community & inclusion, project presentations and teaching. Some findings overlap with existing explorations, for example in the domains of design, debugging and training (e.g., Kim et al., 2021; Villanueva et al., 2021; Wang et al., 2022), but the present research provide details of how these themes are applicable in makerspaces, as well as identify new areas of opportunities specific to makerspaces. For instance, this study identified opportunities for applications that integrate between design and construction processes (such as AR applications that show how 2D laser cut shapes would be transformed into 3D objects or vice-versa); record and replay the process of a student constructing/deconstructing objects; allow constructed objects to be virtually modified (e.g., by changing colors) or annotated (e.g., by leaving design notes); or debug computer programs by physically manipulating the physical objects. Additionally, there are opportunities for AR to educate learners about topics such as psychology (e.g., showing how human brains process interactions with a ball in a maze), chemistry (e.g., showing the chemical process driving the laser cutter), or computational thinking (e.g., showing how similar computational blocks drive different sensors and motors in various devices in the makerspace). Finally, the study identified underexplored opportunities, such as increasing contextualization (e.g., showing how constructed objects would look when surrounded by their final context of use, rather than a makerspace workshop), increasing entertainment (e.g., adding entertaining effects to real objects to enhance user engagement) and increasing community (e.g., connecting current makerspace users to past projects, or to remote users who cannot be physically present). These findings provide specific design ideas for using AR in makerspaces and other environments that involve physical construction of objects. As designers and researchers create AR applications to explore these domains, a better understanding will be generated about the effectiveness and mechanisms for how AR can enhance student learning in makerspaces. Additionally, it is expected that the tools and activities involved in makerspaces will also be changing over time (e.g. through development of more accessible devices such as electronic-textiles and brain-machine interfaces, or through emerging technologies such as generative artificial intelligence, conductive ink electronic printers and biotechnology tools for makerspaces). These changes will introduce new challenges and opportunities that augmented reality technology may be able to address and could be explored through the process of co-designing with students, teachers, and other stakeholders.

5.2. *Implications for involving students as Co-designers*

By engaging students in co-design, this research showed that the process of designing future AR applications can be aided by student involvement. Involving students in the design process can be a source of idea generation and evaluation, as well as a source of personal transformation. Participants were excited and eager to learn and teach each other about new technologies, leading to increased familiarity and sense empowerment. These findings are similar to previous research that shows co-design improves content knowledge and empowerment (e.g., Cockbill et al., 2019; Hyett et al., 2020; Thabrew et al., 2018); however, because our participants had background in education and explored novel technologies, additional themes were found that are not widely documented in previous research. For instance, participants began considering how AR can be used to enhance their curricula. Some participants developed critical opinions about AR technology after the study compared to before. This increased critical thinking is a beneficial effect of the co-design process showing participants the reality of AR technology and is likely due to the experiences of having exposure to a variety of AR experiences, being involved in designing new learning applications, and having used AR software firsthand. Additionally, the results showed that co-designing AR technology together with multiple stakeholders creates logistical challenges such as increased time involvement due to overcoming lack of familiarity with the novel technology, and due to lack of skills in developing AR applications. In the future, AR authoring tools are expected to become easier to use but creating complex AR applications will likely require involvement from dedicated AR developers. For example, similar to our AR authoring platform, we envision the existence of AR authoring tools that allow users to instantiate pre-created 3D objects and place them in the real world while connecting their effects to data from real sensors; however, if students/teachers want to create simulations for new phenomena or create complex interaction effects between AR virtual models and physical objects that are not supported by the software, then engineering knowledge will be needed to create such custom applications. This will require partnerships between educational experts and AR software designers and developers.

5.3. Implications for integrating augmented reality in makerspaces

Finally, this research generated guidelines applicable to AR in makerspace settings. Some of these guidelines overlap with existing research, such as the importance of having adequate support personnel and considering training time and familiarization (e.g., de Jong et al., 2020; Dong & Goh, 2015; Griksaitis et al., 2014). The current study found additional guidelines suitable for makerspace contexts, such as: giving an interactive introduction tied to functional examples from class that use relevant makerspace machinery/objects; accounting for the dynamic physical and social nature of makerspace environment; being mindful of the usage of devices around the space; etc. These guidelines apply for makerspaces but can be extended to other open learning environments where students interact with physical objects and collaborate openly across a variety of expertise levels. Finally, we note that some of our guidelines are applicable to other contexts where AR is used regardless of the configuration of physical spaces or social groupings, such as: being aware of AR hardware battery usage, being mindful of how to make AR presentations, and considering tensions between AR and non-AR curriculum activities. Future research can investigate the wider applicability of these guidelines to other educational contexts that may benefit from AR technology.

5.4. Limitations

There are several limitations of the current research. We acknowledge that this study investigated the impact of co-design with only one type of technology through high-fidelity prototyping; it is likely that working with other technologies and/or other methods of prototyping may yield different impacts on students who participate in the co-design process. Furthermore, the AR application ideas, prototypes, and guidelines generated through this qualitative research have not been formally evaluated, and their generalizability may be limited to the current samples and setting. The findings generated in this study were guided by the structure and content of the existing makerspace course, because students were influenced by what the class assignment required during that week, and by their background, interests, and knowledge they had gained until that point in time. Furthermore, the knowledge of the AR developers on the team, as well as the structure of the AR software used in this study, influenced the types of prototypes constructed and the impact of the co-design process on students.

5.5. Future work

To expand the generalizability of the findings, a more in-depth evaluation in more controlled manner is required. For example, more controlled studies can be executed, measuring student knowledge learning gains, or comparing AR to non-AR prototypes. It is possible that controlled comparisons will find that some of the AR design ideas identified in this research are not effective, or may be more effective if implemented in a non-AR fashion. Furthermore, future research can investigate if the results scale to other contexts beyond our course and makerspace, by specifically evaluating whether these guidelines and application ideas apply to other types of makerspaces, or other types of environments such as traditional physics laboratories or industrial workshops.

Finally, as future researchers and developers scale these findings to other makerspace contexts, there are several considerations regarding technology limitations. First, AR applications are inherently difficult to be constructed for wide open-ended usage, because they need to be programmed to handle detection of various types of physical objects and interactions (for instance, an AR tool may be able to detect cubic shapes but not rounded shapes; or be able to detect objects in clean lighting conditions, but not on a messy workspace), thus the context of use will need to be tailored to the AR applications, and vice-versa. Hardware scalability will also be a future consideration: AR headsets are ideal because they allow hands free manipulation which is frequently needed in makerspaces, but they are more expensive and require more storage space and more inaccessible; on the other hand, mobile AR devices allow multiple people to look at the same screen and move around easily, but they require a user to hold the device, and require high quality cameras to integrate AR on environments. Such scalability issues will need to be addressed as AR continues to be integrated into future makerspaces.

6. Conclusion

In this research we investigated the opportunities of AR technology for makerspaces, by engaging in a co-design process within a semester-long makerspace course attended by 18 students over 12 weeks. Six prototypes were generated with seven student co-designers, exploring AR uses for topics such as design, fabrication, programming, electronics, and training. We identified nine areas of opportunity where AR technology can benefit makerspaces, including teaching STEM skills, facilitating construction activities, enhancing contextualization of learning, and debugging. Through example AR applications in each of these areas, we illustrate underexplored opportunities where future designers and researchers can focus their explorations, to improve student efficacy and better understand the impacts and uses of AR technology. Additionally, this study explored how students changed their relationship to AR technology as part of the co-design process. For example, students improved their understanding of technology design, increased their enthusiasm for engaging with makerspaces and AR, and promoted critical thinking of AR technology. This research shows that involving students in co-design has the potential not only for generating new ideas for technology applications, but also to improve student understanding and future engagement with educational technology. Based on this process we provided a framework consisting of 18 considerations and guidelines, under four categories for integrating AR technology into makerspace environments. As teachers integrate AR technology into makerspace activities, this framework can be used to guide different levels of student engagement, ranging from students simply using AR applications, to students creating and co-designing AR technology.

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

The authors declare that they have no competing interests.

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Appendix A, B and C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cexr.2023.100008.

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