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RESEARCH ARTICLE

Understanding the educators' practices in makerspaces for the design of education tools

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Abstract

Makerspaces persist as formal and informal spaces of learning for youth, promoting continued interest in studying how design can support the variety of learning opportunities within these spaces. However, much of the current research examining learning in makerspaces neglects the perspectives of educators. This not only hinders our understanding of educators' goals and how educators navigate makerspaces but also constrains how we frame the design space of the learning experiences and environments. To address this, we engaged in a set of semi-structured interviews to examine the contexts, goals, values, and practices of seven educators across five makerspaces. A thematic analysis of the data identified six key categories of competencies that these educators prioritize including a range of skills, practices, and knowledge, such as technical proficiency, communication, and contextual reflection. The analysis also identified five categories of strategies to accomplish certain goals, such as scaffolding, collaboration, and relationship building. Last, it also shed light on three categories of challenges faced at the student-level, teacher-level, and institutional level. We conclude with a discussion on our insights into how we can broaden the problem space in the design of educational technologies to support learning in makerspaces.

Keywords Makerspaces · Makerskills · Educators

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Introduction

The maker movement has fueled the recent global proliferation of makerspaces, which are typically physical workshop spaces operated by local communities or organizations, such as schools and libraries, where people with common interests come together to create DIY projects using technology, art, and science (Eriksson et al., 2018). Given the interdisciplinary nature of the maker projects and the making processes, makerspaces provide opportunities for learning skills essential for careers in STEAM (science, technology, engineering, arts, and math).

Recognizing the educational potential of makerspaces (Blikstein, 2013), there is a surge in makerspaces aimed to provide early exposure to maker skills for middle school and high school learners (Honey and Kanter, 2013; Austin, 2017; Tucker-Raymond and Gravel, 2019; Fasso and Knight, 2020). These makerspaces emphasize experiential learning through collaborative, project-based activities (Dougherty, 2013). Grounded in constructivist and constructionist learning theories, these hands-on maker activities enable learners to explore and create tangible artifacts while developing a wide range of skills (Halverson and Sheridan, 2014; Harel and Papert, 1991; Kafai, 2006; Martinez and Stager, 2013; Keune et al., 2015; Kafai and Resnick, 1996; West-Puckett, 2014), technical competencies such as using digital fabrication tools (Gershenfeld, 2005), project management abilities through task planning (Iwata et al., 2020), and interpersonal skills like collaboration (Oliver, 2016). Thus, what it means to learn in a makerspace is broad and the goals and purposes of makerspaces can vary greatly depending on their specific contexts and communities (Vossoughi and Bevan, 2014). And while several studies have contributed to our understanding of learning in makerspaces (Keune et al., 2015; Bevan et al., 2015; Gravel et al., 2018), they have mostly focused on the learners, leaving a gap in understanding educators' perspectives (Mersand, 2021).

To address this gap, we conducted an inquiry into educators' practices through semi-structured interviews with seven educators from five different makerspaces. The aim of the study was to gain insights into the educators' practices within makerspaces and how they facilitate learning for their students. Through thematic analysis of the interview transcripts, the study identified common competencies, strategies, and challenges among the educators. These educators possessed various expertise, ranging from digital fabrication to animation to mixed reality application development. The makerspaces catered to middle and high school students and varied in organizational formats, including full-time semester-long courses and after-school biweekly classes. By studying learning in makerspaces across this range of formats and interviewing educators with diverse expertise, we aimed to identify commonalities and differences across the makerspaces.

We examined our interview data through a thematic analysis with six rounds of coding focused on the following three research questions:

RQ1. What types of knowledge, skills, and attributes do educators prioritize in their practices within makerspaces, and why?

RQ2. What strategies do educators employ to facilitate their students' learning and competency-building?

RQ3. What challenges do educators face in their pedagogical practices within makerspaces?

Our thematic analysis resulted in a codebook consisting of six sets of competencies that educators valued most, five sets of strategies they deployed, and three sets of challenges that educators encountered in their practices in makerspaces (Fig. 2). This codebook presents a comprehensive snapshot of educator practices in makerspaces and contributes to the existing literature as a potential framework for further studying makerspace learning.

Our analysis further revealed that educators prioritize diverse knowledge, skills, and attributes in their practices within makerspaces that go beyond mastering technical skills. These include skills such as communication, creative problem-solving abilities, and interpersonal skills like collaboration. Educators emphasized the importance of fostering a creative mindset and self-driven curiosity in learners, while also providing support and scaffolding to help learners persist through challenges. Educators employ various strategies to facilitate their students' learning and competency-building, such as promoting collaboration, guiding learners while also fostering resilience towards failure, and providing opportunities for learners to teach and critique one another. Our analysis revealed interconnected themes between strategies and competencies pointing to ways in which educators deploy strategies to build the competencies (Fig. 7).

Finally, we articulate the discussion of our findings by identifying opportunities for further research on technologies for scaffolding problem-based and project-based learning, collaborative work, supporting communication within makerspaces, and building trust and care within makerspaces. Through this discussion, we aim to lay the groundwork for incorporating the findings on educators' perspectives, practices, and needs within the design of the technologies for makerspaces.

Background

This section situates our research on makerspaces within the existing literature by first discussing the educational potential of makerspaces, followed by a review of studies on the multifaceted learning in makerspaces and HCI technologies for makerspace learning, - all pointing out the need and the gap in understanding educators' practices.

Educational potential of makerspaces

Researchers have long recognized the potential of makerspaces to support the learning of technical skills, STEAM-related competencies, and cognitive and social skills through project-based activities (Gershenfeld, 2005; Martin, 2015). Makerspaces are seen as providing a constructionist environment (Harel and Papert, 1991) for hands-on projects (Bowler, 2014) and experiential learning (Martinez and Stager, 2013), involving experimentation, tinkering (Bevan et al., 2015; Gravel et al., 2018), and playful design activities (Honey and Kanter, 2013). These characteristics foster creativity (Georgiev et al., 2017; Austin, 2017), innovation (Peppler and Bender, 2013), and the maker mindset (Dougherty, 2013) among learners. Bannan (2016) and Iwata et al. (2020) further point out that by providing a forum for working on real-world problems, makerspaces can promote critical thinking, problem-solving, and task-planning skills. Vossoughi et al. (2016) similarly emphasize that makerspaces serve as communal participatory design spaces (Wenger, 1999; Niaros et al., 2017) for co-creation and collaboration (Britton, 2012) between interdisciplinary groups and diverse communities, supporting the learning of socio-cultural values (Vossoughi et al., 2016).

The growing recognition of the educational potential of makerspaces has led to an increase in the number of makerspaces for K-12 learners aimed to create a new generation of innovators (Blikstein, 2013; Anderson, 2012; Thomas, 2014). This organic proliferation of makerspaces led to an emergence of diverse organizational formats for these spaces, ranging from in-school workshops to public libraries to mobile fab labs to independent maker schools (Sheridan et al., 2014). As a result, makerspaces do not have a uniform structure or a prescribed curriculum like the conventional k-12 schools, as their pedagogical goals vary widely depending on the contexts and communities they serve (Litts, 2015).

Given this diversity and the rich potential for learning experiences in makerspaces, it is essential to examine the nature of learning in these spaces from multiple perspectives and study the practices of different stakeholders involved.

Nature of learning in makerspaces

Existing research on the nature of learning in makerspaces focuses primarily on studying the diverse skills learned, including technical competencies, cognitive skills, and social skills. For instance, studies have examined the acquisition of STEAM-related technical skills like 3D fabrication (Hoy, 2013; Moorefield-Lang, 2019), electronics prototyping (Buechley et al., 2008), and programming (Resnick et al., 2009; Resnick, 2014) in makerspaces, highlighting how these spaces support the learning of technical skills while challenging existing conventions and barriers in these disciplines. Makerspaces facilitate interdisciplinary experiences, such as fabricating electronic textiles (Kafai et al., 2014), and provide hands-on learning opportunities to engage learners through the construction of objects and the use of technology (Macann and Carvalho, 2021). Further evidence of this is provided by Sheridan et al. (2014)'s comparative study of three makerspaces that found that engagement and innovation within makerspaces thrive on the multidisciplinarity and diverse learning environments wherein the learning is intertwined with making itself (Sheridan et al., 2014). Similar studies examining the learning in makerspaces have demonstrated makerspaces' ability to foster creativity (Austin, 2017) and serve as a space to instill agency and support social change (Sheridan et al., 2013). Yet, research has pointed to the need to further understand how this multidimensional learning is scaffolded in makerspaces by educators to allow the co-construction of knowledge within the physical, personal, social, and cultural contexts for the learners (Keune et al., 2015; Oguilve et al., 2021; Olivares and Tucker-Raymond, 2020; Calabrese et al., 2017). An understanding of educators' practices is further critical for designing educational technologies for makerspaces as we discuss next.

Educational technologies for makerspaces

Recent research has witnessed a surge in the development of educational technologies and tools to support multifaceted interdisciplinary learning in makerspaces. Educational tools like *Scratch* for programming (Resnick et al., 2009), *MakeyMakey* for electronics prototyping (Shaw, 2012), and *Lilypad* for e-textiles (Buechley and Eisenberg, 2008), are now commonly used to teach young learners computational thinking and making (Richard and Giri, 2019). To augment skill learning, lower the entry barrier for novices, and improve the workflows (Hudson et al., 2016) in makerspaces, researchers have leveraged technological advances in sensing, algorithms, and XR tools to build systems like *WeBuild* (Fraser et al., 2017), *CircuitSense* (Wu et al., 2017), *VirtualComponent* (Kim et al., 2019), *PatchProv* (Leake et al., 2021), and *SmartMakerspace* (Knibbe et al., 2015). Similarly, toolkits like *FabO* leveraged the potential of game-based learning to teach digital and physical fabrication to young learners (Turakhia et al., 2021, 2022b). Going beyond instructional and guidance-based learning approaches, toolkits like the *Reflective Maker* (Turakhia et al., 2022a) and *Reflective Make-AR-In-Action* (Turakhia et al., 2023) support learning makerskills for novices through self-reflection using smart tools and augmented reality environments respectively. However, a close review of these systems indicates that while aimed to support novices in skill learning, they primarily focus on one aspect, which is learning technical skills. Furthermore, these systems are often designed from the perspective of the learners and often miss considering the alignment of values and goals of all the stakeholders of makerspaces, including educators (Fourie and Meyer, 2015; Koh et al., 2018; Moorefield-Lang, 2019). Without a clear understanding of the educators, we limit our potential to design educational technologies that support the actual context in which learning takes place. However, as we will see in the next subsection, there is a gap in existing work on examining educators which needs greater attention.

Examining perspectives on learning in makerspaces

Learner's perspectives

Existing studies examining learners' experiences in makerspaces focus on their acquisition of technical knowledge and skills as they progress from being novices to experts. Much of this work aims to provide educators with insights, strategies, and frameworks to improve the learners' experience and motivation. For example, Litts (2015) comparative study of youth learners' experiences across different makerspaces through the lens of new literacies and constructivist learning theories provide the *activity-identity-community* framework to educators for designing maker activities (Litts, 2015). Similarly, Bevan et al.'s study in tinkering in makerspaces provides the *Tinkering Learning Dimensions* framework to educators for designing activities along four dimensions of engagement, intentionality, innovation, and solidarity (Bevan et al., 2015). To improve creative outcomes for learners, Georgiev et al. (2017) presents a framework to design three types of interactions within makerspaces, namely the human-human, the human-tool/machine, and the human-design object interaction. To design and characterize the social aspects of learning in makerspaces that attract students from art and design, engineering, and liberal arts majors, Hira and Hynes (2018) studied 53 makerspaces in informal and formal settings and proposed the "people, means, and activities" framework for the educators. While these studies and frameworks based on the learners' perspectives provide guidelines for designing learning in makerspaces, they miss out on incorporating the educators' perspectives. By centering our work around educators' objectives, how they facilitate multidisciplinary skill learning, and the challenges they face, we contribute to bridging this gap in our understanding of what facilitates learning in makerspaces.

Educators' perspectives

A review of the literature on educators in makerspaces reveals that much of this work is focused on teacher training and professional development rather than educators' experiences teaching (Stevenson et al., 2019; Oliver, 2016). While this work highlights various pedagogical approaches for educators, we only found a few studies that centralized the emergent pedagogical strategies and perspectives of educators. One study by Otieno (2020), examined three makerspaces and identified how instructors developed pedagogical strategies to: break down and guide projects, support learners' reflective work, enable multiple pathways into activities, develop learners' agency to teach themselves, emphasize the iterative process, and centralize feedback. These insights are important for understanding the roles that educators need to be supported in within designs that integrate into makerspace learning environments. For example, consider the design that supports educators in guiding and scoping learners project work. Further, in Einarsson and Hertzum (2020)'s research working with 14 library maker educators, they identified ways that educators organize their learning activities: around tools or materials, objects to be constructed, topics for learners to focus on, or projects to be completed. Their findings provide a start to how we might begin to facilitate our understanding of how computing technologies could be designed with different goals in mind. For example, consider designs that focus support of designing with wood across fabrication tools (i.e. material focused), or designs that support the exploration of renewable energy within a makerspace (i.e. topic focused). While the findings in these studies are beneficial, they are limited, and even so, we can start to examine how their perspectives could begin to shift how we scope design problems for makerspaces. Additional work, to expand our understanding of educators' pedagogical values and goals, and how they align their teaching strategies to match their values is essential to developing our exploration of the design space. Our work adds to this existing body of research on educators' perspectives by examining another set of maker educators, their strategies for teaching, the competencies they prioritize, and the challenges they experience.

In the following sections, we describe the methods of our interview study with the educators followed by the analysis of the study data. We then discuss the insights from the analysis and how this work bridges the above gaps in the current literature.

Methods

This section outlines the methods employed in our interview study, including the process of recruiting interviewees and conducting the interviews. We provide an overview of the makerspaces and educators' backgrounds and describe our thematic analysis of the interview data, which led to the development of our codebook.

Recruiting interviewees

We utilized a purposeful sampling approach (Emmel, 2013) to select interviewees, targeting makerspaces with diverse organizational formats. This ranged from part-time afterschool temporary makerspaces in libraries serving schools facing systemic inequities, to full-time semester-long permanent maker-schools catering to private school students in our metropolitan area. To recruit educators from these makerspaces, we leveraged existing connections and distributed a call for participation within the makerspaces and through the

Fab Foundation Network.[1] The call invited educators to participate in an interview as part of a larger research investigation focused on understanding teaching goals in makerspaces and co-designing a learning game for middle and high school students. We intentionally sought educators with expertise in various skills taught in makerspaces, such as digital fabrication and XR applications. We also aimed for a diverse range of learning environments in terms of size, program structure, resources, and student population. The educators were compensated for their time. In total, we recruited seven educators from five different makerspaces, two of which had a global presence.

Makerspaces and educators

In this subsection, we provide a synopsis of the seven educators across five makerspaces, using pseudonyms for the makerspaces and acronyms for the educators (see Fig. 1). We provide details about the students' age groups, class sizes, class formats, funding processes, space infrastructure, and teaching philosophies. The outline depicted in Fig. 1 showcases the wide range of makerspace environments in which these educators operated.

Novel school: At Novel, the teaching philosophy and project design draw inspiration from the architectural studio format. Students engage in 3-4 week studio projects related to real-world problems, often involving client-based work and user feedback.

> ***JT*** is a full-time facilities manager and student support coordinator at Novel. With a background in education and 12 years of teaching experience at K-8 schools, JT has contributed to the school's growth over the past 8 years. Their teaching philosophy centers around addressing real-world problems using a design process influenced by an architectural studio mindset.

> ***KG*** is a full-time creative coding coach and AR/VR designer at Novel, with an educational background in computer science and game development. Joining Novel after graduate school, KG has been with the school for 4 years. Their teaching philosophy emphasizes the importance of receiving critical feedback, exploring multiple iterations, collaborating in teams, and building a robust portfolio throughout students' enrollment.

Innovate afterschool: At Innovate, the teaching philosophy focuses on promoting student-driven projects. The introductory courses prioritize design thinking and entrepreneurship, followed by project-based studios covering topics such as robotics and 3D printing.

> ***MO*** is a volunteer course developer and lab instructor for the Innovate after-school program. They work full-time as a senior engineer for a hospital and have about 8 years of teaching experience in higher education. They have been working with Innovate for 6 years since its inception. Their teaching philosophy is to focus on providing foundational knowledge and basics by going through a highly structured project, using simple language, and scaffolding concepts.

> ***BB*** is a part-time mentor and 3D art studio instructor for Innovate afterschool program. Their educational background is in animation, and they began teaching for

[1] The Fab Foundation is "an open, creative community of fabricators, artists, scientists, engineers, educators, students, amateurs, professionals, ages 5 to 75+, located in more than 100 countries in over 1000 Fab Labs. The platform is a curated, interactive directory of these locations."

MAKERSPACES					
Pseudonym	**Novel School**	**Innovate Afterschool**	**Art City Program**	**Mobile Fablab**	**Collab Makerspace**
Student age	**13-18 years**	**12-18 years**	**6-14 years**	**12-18 years**	**14-18 years**
No. of students	**40**	**17**	**25**	**25**	**20**
Class freq.	**daily, 8 hours**	**weekly, 3 hours**	**weekly, 1 hour**	**daily, 1 hour**	**weekly, 1 hour**
Class format	**10-12 weeeks long, design studio**	**12-14 weeks long, foundational courses**	**year long, projects**	**2 weeks long**	**15 weeks long, skill-buliding courses**
Funding	**Tuition**	**Free**	**Free**	**Free**	**Free**
Description	**New View School**'s tuition-based program maintains a 1:8 teacher-to-student ratio and is located at a 4,700 sq ft dedicated makerspace, which includes a fablab with digital fabrication tools (such as laser cutters and 3D printers), a photography studio, and a mixed reality studio.	**Innovate Afterschool** is a non-profit afterschool program aimed to teach design, engineering, and entrepreneurship to underrepresented students. The organization doesn't have its own dedicated space and works out of spaces at local schools and public libraries, including a makerspace.	**Art City** is an educational nonprofit organization focused on integrating creative education in public schools. The program does not have a dedicated space and use the space at their partner schools.	**Mobile Fablab** runs a program that partners with local schools to bring educate students. The mobile fablab is a 250 sq ft trailer stocked with CNC, laser cutter, vinyl cutter, 3D printers, microelectronics, and computers. All equipment is transported into classroom space at each partner school, which varies in size and layout.	**Collab Makerspace** is a collaborative workspace dedicated to preparing students for a career in design and engineering. The space is used for 2 classes.
Interviewed Educators	***JT:*** *is a full-time facilities manager and student support.* ***KG:*** *is a full-time creative coding coach and AR/VR designer*	***MO:*** *is a volunteer course developer and lab instructor* ***BB:*** *is a part-time mentor and 3D art studio instructor*	***AD:*** *is the former director of creative programs*	***AM:*** *works full-time as the manager of instruction and senior manager of educational programs*	***DM:*** *is the career technology education makerspace teacher*

Fig. 1 A synopsis of the seven educators across five makerspaces that we interviewed

Innovate after finishing their undergraduate education. They have taught for the organization for 2 years. Their teaching philosophy is to provide students the foundational knowledge at first and let their passions direct growth, where not everyone learns everything. They prefer to bring students into the loop of figuring things out instead of the instructor needing to know everything.

Mobile makerspace: The Mobile Makerspace aims to design digital fabrication learning experiences to engage and inspire students through STEM career paths. The program is free for students through grant support, and free for school for 3 years, after which it costs 10,000 USD for programming.

AM has worked full-time as the manager of instruction and senior manager of educational programs for Mobile Makerspace for 4 years. With an educational background in neuroscience and 7 years of experience in education, primarily with science centers and aquariums, AM follows the five E's of Inquiry-Based Learning (Engage, Explore, Explain, Elaborate, and Evaluate) in their teaching philosophy. They believe that engagement and trust are crucial for learning and act as facilitators, designing activities that quickly involve students in more focused projects while also providing opportunities for choice and self-expression.

Arch City: The teaching philosophy of Arch City is to ignite students' imaginations, support social-emotional well-being, and deepen academic learning, with a heavier emphasis on the connection between design, community, and activism.

AD served as the former director of creative programs at Arch City. With a background in literature and architecture, AD brings 18 years of experience in education, including 1.5 years at Arch City. Their teaching philosophy involves avoiding rigid projects and instead engaging students in interdisciplinary endeavors that offer various paths and ample opportunities for creativity. AD believes in being a partner and facilitator rather than an authority figure, actively engaging with students throughout the learning process.

Collab makerspace Their teaching philosophy is having a collaborative workspace where students explore experiential learning, increase their college and career readiness, and create projects with STEM tools.

DM is the career technology education makerspace teacher for Collab Makerspace, with a background in urban planning and design, and 15+ years of experience in maker education. They have worked with the Collab Makerspace for 3 years and their teaching philosophy follows interest-based learning, peer-to-peer learning, and project-based learning, with a high emphasis on having students be masters of certain techniques and building their confidence.

Interviews

We conducted semi-structured interviews with each educator, lasting between 90 to 120 min. The interviews were conducted remotely using video conferencing and were recorded for analysis purposes. The interviews were divided into two parts: the first part focused on the educators' experiences teaching maker skills, while the second part gathered their feedback on co-designing an educational game for teaching fabrication skills. For this paper, we report the analysis from the first part of the interview, where we discussed the educators' teaching philosophies, curriculum and teaching methods, experiences with students, assessment of outcomes, and challenges encountered.

Thematic analysis & codebook generation

We began our analysis by generating transcripts of our Zoom interviews. To ensure accuracy, we reviewed these transcripts with their corresponding video footage, correcting the transcription errors. We then segmented each transcript into discrete content-based responses, resulting in over 240 response quotes from the interview data.

We then delved into an iterative process of codification and thematic analysis. Three researchers on our team conducted the coding and analysis using Braun and Clarke (2006)'s six-phase thematic coding process, which involved familiarizing ourselves with the data, generating initial codes, searching for macro and micro themes, reviewing potential themes, defining and naming the themes, and producing the final report. In the early stages of thematic analysis, our goal was to gain an understanding of the learning goals, educational strategies, and challenges associated with educators' practices in makerspaces.

COMPETENCIES					
Technical Skills	**Creative Mindset**	**Sense of Agency**	**Communication Skills**	**Contextual Reflection**	**Self-expression**
Tool expertise: the knowledge of different tools (software & hardware), the skills to use them correctly, and a clear understanding of choosing the right tools for the right tasks.	**Creative problem solving:** the ability to frame and break down problems in novel ways to develop creative solutions, and the understanding of how to plan and implement the novel solutions	**Self efficacy:** having confidence in one's skills and proficiencies	**Communicating Ideas:** the ability to describe their design concepts, vision for solutions, and the project goals, and articulate the comprehensive plans for executing the solutions.	**Social contextualization:** the ability to critically situate and socially contextualize the design ideas, and reflect on the impact of their solutions on different social groups and communities	**Self-expression:** the ability to spontaneously and freely express their individuality and uniqueness in their design solutions
Solution design and development: the ability to plan out the steps and implement them to produce solutions	**Diversity mindset:** the ability to understand a problem through multiple viewpoints, accept the difference in perspectives in others, and be able to receive and feedback from others	**Self-driven learning:** the independence to seek solutions on one's own, and leanring through metacognition strategies	**Process documentation:** the ability to document their design implementation journey and present it orally and visually	**Personal contextualization:** the ability to examine their designs with respect to oneself, and articulate how their ideas reflect their personal journeys, goals, and values	
	Curiosity and play: the ability and eagerness to engage in inquiry and explore design and fabrication in a playful way	**Agency:** the ability to make decisions on one's own with confidence in their choices, and to take ownership of their projects			

STRATEGIES				
Scaffolding Learning	**Encouraging Failure**	**Fostering Collaboration**	**Building Relationships**	**Assessing Performance**
Through problem scoping: by widening the scope of the project over time starting with a limited scope, then adding flexible components, then widening to an open-ended scope	**Through teaching iterative design:** teaching overcoming the fear of failure and teaching the importance of failing fast and failing early	**Through organizational interventions:** by enforcing engagement in a structured way	**Through direct student-teacher engagement:** improving trust and engagement with the students	**Through personalized metrics:** For technical and soft-skills by assessing on individual growth and improvement over time instead of fixed standards and metrics for technical skills instead of using a one-size-fits-all approach
Through project stages: by incrementally teaching skills through project stages incrementally from brainstorming to documenting to skill-learning to final presentation		**Through spatial interventions:** by re-designing seating and spatial setups of the classrooms or makerspaces to build organic collaborative interaction	**Through catalystic role:** for facilitating interaction, engagement and building trust between students	**Through learner-defined outcomes:** of the deliverable choices, quality and by offering open-ended options for deliverable media/form(?)
Through progression of concepts: incrementally introducing complex concepts over time, by first introducing low-level technical skills and then high level design concepts				
Through adapting support and resources: by providing more support in the beginning to then providing more autonomy as the students learn the skills				
Through metaphors: by teaching complex concepts using analogies with concepts familiar to the individual learners instead of trying the one-size-fits-all approach				

CHALLENGES		
At Student Level	**At Teacher Level**	**At Institutional Level**
Increasing Student engagement: [description]	**Adapting the Content delivery and pace** [description]	**Training teachers** [description]
Instilling Confidence : [description]	**Personalizing the assessment of soft-skills:** [description]	**Increasing Buy In/Support :** from the students and the school boards
Improving Interpersonal Relationships: [description]		**Finding Resources:** shortage of time, tools, funds, and human resources

Fig. 2 An overview of our codebook sectioned into the above categories of competencies, strategies, and challenges, and their sub-categories

As we progressed through the analysis, we aimed to uncover more nuanced and detailed themes that could address our research questions listed in Sect. 1.

To start, we familiarized ourselves with the data by listening to the video recordings and the machine-generated transcriptions. Each researcher was then assigned 2–3 interviews to highlight, comment on, and label. At least two researchers independently coded each interview quote, and we then exchanged notes and provided feedback on the labels. Following this initial round of familiarizing ourselves with the data and labeling it, the three researchers on our team engaged in discussions to identify commonalities between the comments and labels independently written by the researchers, and finalized the three emerging macro-categories: Competencies, Strategies, and Challenges.

For the next rounds, two members of our research team further re-coded the data, identifying emerging micro-themes. The interrater reliability test was employed to maintain consistency in coding and ensure that the interviews were appropriately tagged with the emerging themes. The third team member continued to engage in peer debriefing, challenging interpretations, and facilitating the refinement of the themes through critical discussions Lincoln and Guba (1985); Spall (1998). Throughout the process, we completed six iterations of refining the codes, achieving inter-rater agreement of over 80% for each iteration. After 80% agreement was established, disagreements were resolved through discussions between the coders. During these rounds of refining the themes, we were also mindful of framing our findings in a structure that would provide valuable insights for researchers interested in developing educational tools for learning in makerspaces.

Our analysis resulted in the emergence of six themes related to competencies, five themes related to strategies, and three themes related to challenges. These findings are detailed in the next section.

Findings

Our thematic analysis resulted in a codebook sectioned into three macro-themes: *Competencies*, *Strategies*, and *Challenges* (Fig. 2). While not exhaustive or identical across educators or makerspaces, this codebook gives an overview of the educators' perspectives and experiences and is possibly indicative of more prominent themes of educational practices within makerspaces.

Competencies

We identified six sets of competencies (see Fig. 3) including: technical skills focused on the tools and the ways they're used to solve problems, communication skills revolving around students' ideas, solutions, and processes, skills in students ability to be open and take on a creative mindset, skill in students' reflectivity on their work and how it's situated in the world, ability to act with agency, and the ability for learners to engage in self-expression. We identify the nuance in how the educators discussed the various competencies.

Building technical skills

Educators referenced the importance of building technical skills the most out of the set of competencies they discussed. The educators wanted their students to *"to know their tools and their materials, and especially know when to use the right tool, the right material for the right purpose."*-[AD] Examples of **Tool expertise** included a range of skills from 3D modeling and digital fabrication to programming and electronics prototyping to XR design and creative writing. Importantly, building technical skills meant going beyond the knowledge of tool expertise and involved knowing when and how to integrate their various tools and components to achieve their goals. MO, for instance, said that,

COMPETENCIES: Description	Example Quotes
Technical Skills	
Tool expertise: the knowledge of different tools (software & hardware), the skills to use them correctly, and a clear understanding of choosing the right tools for the right tasks. *(Examples of skills include programming, electronics, 3D modeling, digital fabrication, sewing, AR/VR design, creative writing.)*	*"I want them to know their tools, their materials, and especially know when to use the **right tool**, the **right material** for the **right purpose**." [DM]* *"learn how the **components fit together.** On an elementary level [we teach] them how to **put mechanical pieces together**. We then sit down with them as they're trying to figure out, `the thing needs to move this way', and then we would talk about, what kind of actuators might be useful for that?"-[MO]*
Solution design and development: the ability to plan out the steps and implement them to produce solutions	*"it's about **behaviors**, **thinking routines**, and **problem solving techniques** that they use the doing the projects and learning the tool"-[DM]* *"the **design process**, know **who's** your **client**, **how** [to] **approach the problem**, and **what tools** have you got [...] taking pieces of the big problem and boiling them down into something that can be coated with the available resources"-[MO]*
Communication Skills	
Communicating Ideas: the ability to describe their design concepts, vision for solutions, and the project goals, and articulate the comprehensive plans for executing the solutions. *(Examples: oral descriptions, visual presentations through sketches, diagrams, storyboarding, 3D models, animations, and videos.)*	*"Communication happens on **every level**. [The students] need **to communicate the creative side** of what [they] are doing, such as the scale or the craft, as well as the conceptual, such as the intentional content." [AD]* *"A **storyboard** that explains the VR **experience** or it's the storyboard that shows each **scene** of your story that you're writing or it's a storyboard that shows **how the device is going to be** used and who benefits from it. The same goes for diagrams" [KG]* *"**Critical communication**, which is about the presentations about your applied writing skills and data comprehension" [KG]*
Process documentation: the ability to document their design implementation journey and present it orally and visually *(Examples of describing the process included story boarding, prototyping, 3D modelling, animating, sketching, etc.)*	*"[the students] can tell me a **story** about [their project] and they could **document** that they tried [the solutions]. It's not always clean cut" [DM]* *"I did a whole thing around swapping [students'] notebooks so they could kind of **see how other people are documenting** a similar project" [MO]* *"We have a lot of documentation because we're kind of obsessed with **the process rather than the final result.** It's like what did you do in order to get there. So even if the end you didn't you know achieve what you were set up setting out to do **if you document it and explain** everything you explored along the way, that's a core skill" [KG]*
Creative Mindset	
Creative problem solving: the ability to frame and define problems in novel ways to develop creative solutions, synthesize knowledge across diverse fields	*"creative mindset is skills like **design research** and iteration and **concept building**" [KG]* *"we follow a **creative mindset**, as opposed to a knowledge mindset [...] it's not about copying what's there and engineering it [...] but about **solving a particular problem using abstraction** [figuring] out what the problem is how to self-define it" [AD]* *"**synthesis of knowledge**, bringing knowledge from disparate places together [for example] how biology might relate to something like designing superheroes, [...] begin to relate these fields to one another, not in a prescriptive way, but understanding that multiplicity of viewpoints is valuable" [AD]*
Diversity mindset: the ability to understand a problem through multiple viewpoints, accept the difference in perspectives in others	*"**sharing ideas** and **multiplicity of views**, being able to realize that there are ideas outside of yourself that are just as valuable as the ideas that you have internally" [AD]* *"a core skill we want to build is, how you **give feedback**, how you **receive feedback and critique**" [KG]*
Curiosity and play: the ability and eagerness to engage in inquiry and explore design and fabrication in a playful way	*"not getting discouraged by failure and following unexpected avenues of discovery" [AD]* *"nurturing students wanting to go above and beyond, they really love [fabricating] something customizable and pushing the envelope" [BB]*
Contextual Reflection	
Social contextualization: the ability to critically situate their design ideas in different social contexts, and reflect on the impact of their solutions on diverse social groups and communities	*"really understanding that whatever work that you're doing **falls within a body of work and humanity,** [...] that can be history, or that can be cross cultural information. [We use] art and creativity and as a tool to get into **social emotional learning and social justice and equity**." [AD]* *"Social contextualization of the project, **cultural and historical awareness**, **empathy and civic participation**" [KG]* *"it's knowing that the different digital fabrication tools, as a way to solve problems are the way to affect **change in their community** or in themselves or in something they're interested in." [DM]*
Personal contextualization: the ability to examine their designs with respect to oneself, and articulate how their ideas reflect their personal journeys, goals, and values	*"The students have to feel **proud** about the work that they did" [KG]* *"We try to engage with a range of concepts as artistic pursuits. That's partly intentional so [the students] get a breadth of exposure and perhans hit on something that they are **very passionate about**" [JT]*
Sense of Agency	
Self efficacy: having confidence in one's skills and proficiencies	*"I try to get them more **confident in their skills** so when they advance to complex things so they won't be totally intimidated" [DM]* *"We leave the students be and give them this **independent opportunity** [...] to **lead a lecture** on this thing that you know and teach all of us how to use it" [KG]*
Self-driven learning: the independence to seek solutions on one's own, and learning through metacognition strategies	*"I just gave them a sewing machine and said, 'here's a step by step, of how to set it up, but I want you to look at it and the labels and [...] **figure out what each of these things do**' " [DM]* *"I can help the students along to a certain point, but there are certain things that they will encounter a problem in, and sometimes it's a learning experience from it. [In those] scenarios, **it's not beneficial to just give them the answer.**" [BB]* *"If they're not willing to **take the effort to go and try to solve the problem themselves** before they come for help, that's something that I think students need to learn. [As coaches], we had to teach [the students] to be independent and we couldn't give them the answers. " [KG]*
Agency: the ability to make decisions on one's own with confidence in their choices, and to take ownership of their projects	*"A big part of the creative agency is that **you don't have to follow feedback** that's given. But you should **know when it's right to follow feedback** or not right to follow feedback because you know it doesn't fit your vision." [KG]*
Self-expression	
Self-expression: the ability to spontaneously and freely express their individuality and uniqueness in their design solutions	*"when the student can say **'this is my thing, I customized it, I made it'** that's where [the students] are going to shoot for the stars [...] **they push it because it's their thing**, and they want to make it look cool" [BB]* *"the kids are more **inventive** about what they care about. It's about **expressing something they care about** and they probably will be more excited to finish it." [DM]*

Fig. 3 We list the six sets of competencies that educators aimed to teach in makerspaces along with their corresponding quotes from the educators

"On an elementary level [we teach] them how to put mechanical pieces together. We then sit down with them as they're trying to figure out the 'the thing needs to move this way,' and then we would talk about, what kind of actuators might be useful for that."-[MO]

The educators expected their students to develop their ability to plan and implement making-related activities through applying their tool expertise to **Solution design and development**. DM, for example, said that,

"It's about behaviors, thinking routines, and problem-solving techniques that they use the doing the projects and learning the tool"-[DM]

The tools are seen as part of a design process that involves a context in which learners must,

"know who's your client, how [to] approach the problem, and what tools have you got [...] taking pieces of the big problem and boiling them down into something that can be coated with the available resources"-[MO]

Learners' knowledge of the tools should be integral to how they examine their problems and craft solutions.

Communication skills

Educators also wanted their students to build communication skills where they could communicate their design ideas and visions for solutions and document their processes of making through various mediums, from drawing, presentations, storyboarding, etc. Educators recognized the diverse nature of what learners needed to communicate about:

"Communication happens on every level. [The students] need to communicate the creative side of what [they] are doing, such as the scale or the craft, as well as the conceptual, such as the intentional content."-[AD]

The documentation of their ideas also included the ways in which their designs were situated with people in real contexts. For example, KG makes this apparent in their discussion of storyboards,

"A storyboard that explains the VR experience or it's the storyboard that shows each scene of your story that you're writing or it's a storyboard that shows how the device is going to be used and who benefits from it."-[KG]

The documentation was also essential to emphasize for the educators because, *"the process was more important rather than the final result"-[KG]*, and they wanted the students *"to document and present the story of how they got to their solutions, and what they explored on the way."*-[KG]

Creative mindset

The second most frequently cited set of competencies was developing a creative mindset. This involves learners being able to think dynamically and reatively during the process of problem-solving, being able to take into consideration a diversity of perspectives, and being able to engage in curious and playful inquiry. Creative problem-solving skills involve *"design research and iteration and concept building"*-[KG]. One educator contrasted this approach to problem-solving with a knowledge mindset,

> *"we follow a creative mindset, as opposed to a knowledge mindset [...] it's not about copying what's there and engineering it [...] but about solving a particular problem using abstraction [figuring] out what the problem is how to self-define it"*-[AD]

This abstraction requires that learners are able to think across various knowledge bases. As one instructor put it, it's about,

> *"synthesis of knowledge, bringing knowledge from disparate places together [for example] how biology might relate to something like designing superheroes, [...] begin to relate these fields to one another"*-[AD]

Educators focused on developing a diversity mindset in their students for synthesizing knowledge and *"making connections between disparate fields"*-[AD] and analyzing problems with multiple perspectives. Besides sharing these ideas and multiple viewpoints, the educators wanted their students to realize that *"there are ideas outside of [themselves] that are just as valuable as the ideas that [they] have internally"*-[AD]. Further, at the same time, they should recognize the importance of the reciprocity of feedback—*"a core skill we want to build is, how you give feedback, how you receive feedback and critique"*-[KG].

It was important to the educators that the students engaged in this creative inquiry with curiosity and playfulness because they believed that this playful approach would enable students to discover unexpected avenues of solutions. This involved, *"not getting discouraged by failure and following unexpected avenues of discovery"*-[AD]. They wanted learners to be able to be excited to continue their exploration, thus it was important for them to be *"nurturing students wanting to go above and beyond, they really love [fabricating] something customizable and pushing the envelope"*-[BB].

Contextual reflection

Educators also wanted their students to learn to contextualize the work, both with respect to the broader society as well as the self. With respect to the broader situativity of the learners' work they wanted them to,

> *"really understanding that whatever work that you're doing falls within a body of work and humanity, [...] that can be history, or that can be cross-cultural information. [We use] art and creativity and as a tool to get into social-emotional learning and social justice and equity"*-[AD]

The educators noted the importance of, *"Social contextualization of the project, cultural and historical awareness, empathy and civic participation"*-[KG]. This created a link to the technology in the space and the strength educators saw in what learners could create:

> *"It's knowing that the different digital fabrication tools, as a way to solve problems, are the way to affect change in their community or in themselves or in something they're interested in."*-[DM]

The educators wanted their students to not only critically situate their design ideas and reflect on how their solutions would impact different social groups and communities, but also examine how their work represented their own values and goals. The educators wanted learners to engage in work that ignited their passions, and at the end of the day, *"The* *students have to feel proud about the work that they did"*-[KG]. To help build connections to the learners' interests JT states that they,

> *"try to engage with a range of concepts as artistic pursuits. That's partly intentional so [the students] get a breadth of exposure and perhaps hit on something that they are very passionate about."*-[JT]

Sense of agency and expression

Educators also emphasized the importance of empowering students with a sense of agency and self-efficacy and the ability to drive their own learning experiences. This confidence was seen as essential to their growth as makers, *"I try to get them more confident in their skills, so when they advance to complex things so they won't be totally intimidated"*-[DM]. Sometimes this was done through the learners being placed in positions of leadership:

> *"We leave the students be and give them this independent opportunity [...] to lead a lecture on this thing that you know and teach all of us how to use it"*-[KG]

Further, they put the learners in positions where they would have to drive their own learning with only a little guidance. As DM recalls,

> *"I just gave them a sewing machine and said, 'here's a step by step, of how to set it up, but I want you to look at it and the labels and [...] figure out what each of these things do"*-[DM].

BB reflected on the importance of this,

> *"I can help the students along to a certain point, but there are certain things that they will encounter a problem in, and sometimes it's a learning experience from it. [In those] scenarios, it's not beneficial to just give them the answer."*-[BB]

Educators explained that they wanted their students to develop self-efficacy and confidence in their skills because,

> *"a big part of the creative agency is that [the students] don't have to follow feedback that's given. But [they] should know when it's right to follow feedback or not because it doesn't fit [their] vision"*-[KG].

Building further on this sense of agency, educators wanted their students to be able to confidently explore their passions and be,

> *"more inventive about what they care about. It's about expressing something they care about and they probably will be more excited to finish it."*-[DM].

Strategies

We identified five categories of strategies (see Fig. 4) that highlight how educators scaffold learning, foster collaboration, support building relationships, assess performance, and encourage learning through failure.

STRATEGIES: Description	Example Quotes
Scaffolding Learning	
Through problem scoping: by widening the scope of the project over time starting with a limited scope, then adding flexible components, then widening to an open-ended scope	*"Each of our courses is framed as a studio with **specific prompts** thats addresses a real world problem in either a very **direct sort of clientbased way** where we're getting user feedback about something thats meant to help specific functions, or in a **broad or whimsical or conceptual way** as in doing the future world building. What would a dystopian world look like? How would you make the devices that might help you adopt a really extreme conditions in such world." [JT]*
Through project stages: by incrementally teaching skills through project stages from conceptualizing to documenting to skill-learning to final presentation	*"there's **a specific set of skills for each subject**, I know that the students need X for modeling, Y for texturing and so on. If they have these aspects then they can get started the project, which leads the design week. Depending on the complexity of [the project], the first week or so is focused on getting them the tools at the start of the projects, " [BB]*
Through progression of concepts: incrementally introducing complex concepts over time, by first introducing low-level technical skills and then high level design concepts	*"We have a **two week skill building at the beginning** of the semester **for new students** that involves **hand fabrication skills** with just cardboard box cutters, glue, and paper. And then **from prototyping into digital fabrication** and then, we get into **more complicated** [aspects] like mechanical motion and **how you design that** in CAD software, then you can 3D print parts. And then students can **take the rhino skills and apply them into 3D world**, which we can use in games. " [KG]*
Through adapting support and resources: by providing more support in the beginning to then providing more autonomy as the students learn the skills	*"So I almost always **start with something very simple** where they light up something very quickly and they **learn some of the basics** like what is a circuit. Or what is **reverse engineering**, so we always do a take apart. And **so I build up their confidence**, before I put them in front of the computer and the laser cutter." [DM]*
Through metaphors: by teaching complex concepts using analogies with concepts familiar to the individual learners instead of trying the one-size-fits-all approach	*"I tend to engage the [students] that are like "I'm never going to go to college, I don't even know what engineering means, I'm failing math and science and so I'm not good at that stuff." But at the same time, they are natural makers, they are interested in building their own things they are inventive in and with materials, especially in creative you know about like economics of that kind of stuff." [DM]*
Fostering Collaboration	
Through organizational interventions: by enforcing engagement in a structured way *(Examples cited include, enforcing working in teams, interdependent groupwork, tool-sharing, etc)*	*"The group size is typically student pairs. Two students working on a project, or a group of five is probably the largest a group would be." [KG]* *"we shifted to having the kids work in pairs mostly, because our observation was pairs work best" [MO]* *"I ask the students, 'everybody turn your computer's towards so that you can all see each other's. I want you to go through and figure out which design you think is not necessarily' "-[AM]*
Through spatial interventions: by re-designing seating and spatial setups of the classrooms or makerspaces to build organic collaborative interaction *(Examples cited include making students with complementary skills to sit closer to each other)*	*"we were very much **deliberate in the design of [the classroom] space** so there [..] was a lot of how do you push people to start teaching themselves and **then turn to the person next to them and start teaching them** and then like creating that **learning community together.** From there it's much better if they start showing each other, start innovating, and working on the things that they want." - [DM]* *"Because they're **sitting really close**, they talked a lot with each other about programming stuff." [BB]*
Building Relationships	
Through direct student-teacher engagement: improving trust and engagement with the students	*"There's a lot of like **trust building** and getting to know them. And in the beginning, and I find it easier to do with offline like projects like doing sewing, cardboard engineering, and fast prototyping" [DM]* *"it was really just creating **a welcome environment to mess up**. I'm very goofy when i'm educating. So, they think [they] can mess up in front of [me], and so it becomes a very inclusive and engaging environment."-[AM]*
Through catalystic role: for facilitating interaction, engagement and building trust between students	*"The groups are intended to be roughly 50/50 boys and girls-the social elements of it, [...] I think is important."-[MO]* *"A lot of times **the early projects are team based** project challenges, so that they start **learning to communicate with each other** and **sharing the tools**, because later, especially with the digital fabrication tools with one laser cutter, they have to learn to share."[DM]*
Assessing Performance	
Through personalized metrics: For technical and soft-skills by assessing on individual growth and improvement over time instead of fixed standards and metrics. for technical skills instead of using a one-size-fits-all approach	*"I'm **not going to compare** something that a student who just came in made to someone with five years [experience], on the same level." [BB]* *"There is like **a lot of disparity in the skill levels**, and we want to try to bring everybody up to the same level, but that can be very difficult, not just for teachers, but also for like the students themselves. So we have been working to not only scaffold all of the students but also **to adjust expectations right"**- [KG]*
Through learner-defined outcomes: of the deliverable choices, quality and by offering open-ended options for deliverable	*"if I design a curriculum and I know what students are going to do, and they produce what was in my my head, then something went wrong" [AD]*
Encouraging Failure	
Through teaching iterative design: teaching overcoming the fear of failure and teaching the importance of failing fast and failing early, through tinkering	*"I start with the art of tinkering and some work from agency by design around maker centered learning and learning thinking routines. I want [the students] to do iterations, and learning a design cycle, as a way to keep fixing the problems and tinkering." - [DM]* *"not getting discouraged by failure and following unexpected avenues of discovery" [AD]*

Fig. 4 We list the five sets of strategies that educators deploy to foster the learning of these sets of competencies in makerspaces. This table also provides the corresponding quotes from the educators

Scaffolding learning

The most prominent theme in educators' interviews was how they discussed scaffolding learning to support learners' development of competencies. Based on their teaching goals and philosophies, educators scaffold learning in varied ways, such as through scoping the problem, teaching skills incrementally across project stages, progressively introducing concepts of increasing complexities, adapting resources and giving students more autonomy over time, and teaching complex skills using metaphors and analogies.

Project scoping allowed educators to introduce new concepts and skills in a well-defined experience so the students do not feel overwhelmed. As the students got more acquainted with the skills, the educators widened the scope of the projects. Similar scaffolding involved incremental teaching of skills as the students progressed to different project stages. For example, JT said that they are intentional in the way they introduce technology

> *"Starting with hand fabrication because moving into digital fabrication too soon can sometimes be a bit of a fall for students as they aren't aware of the work times that would be involved. So students who are still evolving need to grasp the long-term thinking concepts and project management pieces. They need a lot of scaffolding and support."*-[JT].

This approach of progressively introducing complex concepts starting with low-level technical skills and then teaching the broader high-level abstract concepts allowed educators to intertwine the learning of technical skills with other competencies like contextualization and developing a creative mindset.

The scaffolding also enabled teachers to adapt support, resources, and expectations to mitigate the differences in students' skill levels. The educators,

> *"want to try to bring everybody up to the same level. If [the educators] are working with some highly skilled students and some students who are newer then [they] will push the project for those highly skilled students even further and for the younger students who are fairly newer students, the expectations are that [the students] get [the project] done even if with only one prototype."*-[KG]

Fostering collaboration

Fostering collaboration was the second most cited strategy. Educators deployed deliberate organizational interventions like group work and spatial interventions like classroom design to increase opportunities for direct and organic collaboration. Concerning group work, educators observed that the dynamics of students' interactions and learning were impacted by the group size. For example, DM said,

> *"We were very much deliberate in the design of [the classroom] space so there was never somebody standing up at the front and presenting. It was a lot of how do you push people to get them excited and start teaching themselves, then turn to the person next to them and start teaching them, and then create a learning community together."*-[DM]

The educators recognized that the social interaction resulting from formal and informal collaborations is instrumental in developing the learning community within makerspaces. Much of the learning of communication and developing a creative mindset relied on fostering collaboration, according to educators.

Building relationships

What further developed from fostering collaboration was the goal to establish a stronger sense of community among students. To achieve this, educators also focused on building relationships to increase trust and engagement with and among students.

The educators had several ways of establishing relationships, ranging from *"trust building by getting to know them"*-[DM] to *"creating a welcome environment to mess up by being goofy"*-[AM]. To build trust with the students, DM recognized how engaging in the maker activities with the students can be helpful as they said,

> *"In the beginning, it is easier to [build trust and relationship] with [the students through] offline projects like sewing, cardboard engineering, and fast prototyping"*-[DM]

Educators also played a catalytic role in students building strong relationships among themselves through project design, and sharing of tools and spaces. DM further added that,

> *"the early projects are team-based challenges, so [the students] start learning to communicate with each other and sharing the tools."*-[DM]

The educators state the importance of building a sense of trust with the students and building a sense of community among students as it leads to a more positive learning experience for the students as well as a fulfilling teaching experience for the educators.

Assessing performance

Another strategy deployed by educators is to use personalized metrics for evaluation and assessments of students' performances where they emphasize more on every learner's individual growth and progress rather than using a standardized metric of evaluation for everyone. Using personalized metrics and avoiding a one-size-fits-all scoring is particularly useful in makerspaces where the learners come in with diverse interests, backgrounds, skillsets, and expertise. For example, BB said,

> *"I'm not going to compare something that a student who just came in made to someone with five years [experience], on the same level."*-[BB].

Similarly, KG pointed out that educators also needed to adjust their expectations right in alignment with students' skill levels by saying,

> *"There is like a lot of disparity in the skill levels, and we want to try to bring everybody up to the same level, but that can be very difficult, not just for teachers, but also for like the students themselves. So we have been working to not only scaffold all of the students but also to adjust expectations right."*-[KG].

By making assessments relevant and meaningful to learners, they are more likely to be motivated and engaged in the learning process. The educators also adjusted their outcome expectations and deliverables to align with the wide variety of expertise and skill sets among the learners and at times simply based on how the learner defined what they wanted to do.

CHALLENGES	Example Quotes
At Student Level	
Increasing Student engagement: for projects, inter-class interaction, etc.	*"Collaboration can be tricky, especially in like the digital space, but with maker space kind of maker stuff as well because it's like where's that file who's who's like. How are we sharing the file? It's a big problem when somebody away and their computer has the file or their computers dead. Collaboration with like code right can be difficult because it's like well this student is working on the code, so I don't have anything to do." [KG]*
Instilling Confidence: Increasing proactiveness, self-efficacy	*"kids won't always show up again. They won't show up if you're saying we're going to do STEM. With maker spaces, they're not used to it they're embarrassed by that they don't know [the STEM skills] already. [DM]* *"It's hard to sit in a chair and like focus on one thing, especially if stuffs not going well, or you have creative block. It can be intimidating to talk to people [and ask help]. It would be better* ***to have tools that can help students be self advocating."*** *[KG]*
Improving Interpersonal Relationships: Between students-teachers	*"it's dealing with middle school* ***personalities****. They are wonderful and so creative and just* ***need an adult really to be there*** *to believe in them, and a lot of time, a lot of ways to make them understand that they can do this" [AM]*
At Teacher Level	
Adapting the Content delivery and pace: to personalize for different students and expertise levels	*"we have some students coming in, some students leaving, [so] it's kind of* ***a revolving door****. So we always have to be able to teach new students and* ***catch them up to speed on*** *stuff." [BB]*
Personalizing the assessment of soft-skills: *for different personal growth journeys of every student*	*"that's like a big issue, because when we want them to present what they did it can look like they did very little right in the end if they're just presenting like what they made. But you don't understand that they had like hundreds of drafts and diagrams where they were figuring out [the solution] and that happens with like every project" [KG]*
At Institutional Level	
Training teachers: to increase teacher:student ratio	*So now we're starting to focus more on* ***education and training****, as opposed to kind of curriculum delivering [...] so* ***exposing teachers*** *to how to integrate* ***social justice, equity, and social emotional learning*** *into into whatever their their class work is." [AD]*
Increasing Buy In/Support: from the students and the school boards	*"We are connecting to makerspaces and* ***nobody knew what to do****. So they had all this equipment and I was seeing that people were either just downloading things from Thingiverse and printing them out or they were* ***doing really prescriptive kinds of projects.*** *None of them were aligned with my kind of pedagogy and philosophy which is about the interdependency knowledge and like multimodal approaches." [AD]*
Finding Resources: shortage of time, tools, funds, and human resources	*"It's a lot harder in a program where you're meeting kids one hour a week for 40 minutes and dropping into a program in schools that are* ***underfunded****. We're only in there for an hour a week so it's not really feasible for us to look at the growth of every student which is challenging." [AD]* *"I don't think we've had* ***enough time.*** *The intensive courses, are for two weeks every day in the summertime, or the regular school year sessions are a few hours, once a week for about 10 weeks. Between talking about the design process, learning about that, learning about the coding, trying to build something, and come up with the ideas, and then do a final presentation, you're lucky if you can get fully through one iterative loop with little problem solving things on the way. But not doing a demo, getting a review, and then doing a revision - there just hasn't been enough time for that." [MO]*

Fig. 5 We list the three levels of challenges that educators encounter in makerspaces. This table also provides the corresponding quotes from the educators

Encouraging failure

Finally, through tinkering and iterative design, educators encourage students to actively engage with their ideas and designs. In makerspaces, educators encourage failure, as they see failure as a natural part of the learning process, not as a setback. Educators strove to *"create a welcome environment to mess up."*-[AM] where students feel comfortable taking risks and trying new things, even if they don't always succeed. For educators, it is important that the students,

> *"do not get discouraged by failure and continue following unexpected avenues of discovery"*-[AD].

By failing fast and early through iterative design, quick prototyping, and tinkering, students learn to persevere through challenges and setbacks, which helps build their resilience and determination. Educators also mentioned that they want their students to continue taking risks while innovating by continuing

> *"to do iterations, and learning a design cycle, as a way to keep fixing the problems and tinkering."*-[DM]

Challenges

We categorized the identified challenges at three levels—student, teacher, and institutional. Student-level challenges include maintaining students' attendance, engagement, and confidence in the program. Teacher-level challenges include constant personalization and adaptation of the content delivery and pace of teaching for individual learners. While educators also face institutional-level challenges like training more teachers, finding sufficient resources, and gaining support from outside sources like school boards, we focus on the first two challenges for the scope of this paper Fig. 5.

Student-level challenges

At the student level, the educators faced several challenges ranging from increasing student engagement in classrooms, to instilling confidence and improving interpersonal personal relationships between students and teachers. DM, who works with students from communities facing systemic inequities, points out that

> *"Kids won't always show up again. They won't show up if you're saying we're going to do STEM but if you [say that] we're going to make a robot that can help you do X, Y & Z, they come in"*-[DM].

Instilling confidence, especially when students are experiencing roadblocks can be challenging as KG points out for students,

> *"It's hard to sit in a chair and focus on one thing, especially if stuff's not going well, or you have a creative block. It can be intimidating to talk to people [and ask for help]. It would be better to have tools that can help students be self-advocating."*-[KG]

Lastly, the educators noted the importance and difficulties of creating supportive relationships that could facilitate learners in persisting through challenges.

Teacher-level challenges

At the teacher-level, the challenges include constant personalization and adaptation of the content delivery and pace of teaching for individual learners. KG shares that,

> *"I think not being able to check in with every student not being able to understand [is a challenge]. I want them all to be at a certain point, but by the end of the day, I don't necessarily have time to check to make sure that they all get there or help all of them if they're encountering issues or like even knowing like okay this person got stuck on like a five-minute fix but they've been waiting 25 minutes."* - [KG]

Further, being able to assess and communicate the growth that various learners achieved can be challenging when the output might not be as indicative of their progress.

Competencies

Strategies	Technical Skills	Creative Mindset	Sense of Agency	Communication Skills	Contextual Reflection	Self-Expression
Scaffolded Learning	58.10%	41.89%	32.43%	2.70%	0.27%	21.62%
Encouraging Failure	27.77%	55.55%	38.88%	22.22%	0.00%	5.55%
Fostering Collaboration	51.85%	37.03%	29.62%	55.56%	3.70%	3.70%
Building Relationships	40.90%	54.54%	59.09%	18.18%	9.09%	18.18%
Assessing Performance	76.19%	28.57%	38.09%	38.09%	4.76%	4.76%

Percentile by Row: 1% – 99%

Fig. 6 The frequency of the co-occurrence of themes of competencies and strategies

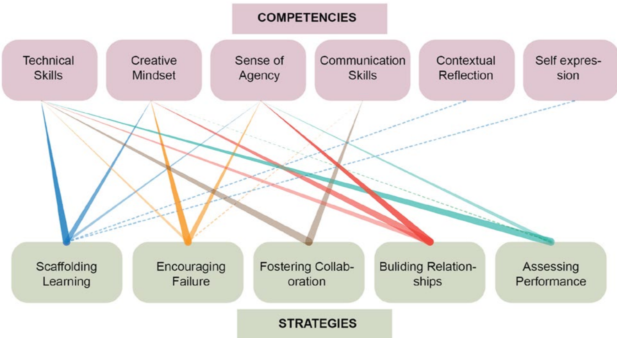

Fig. 7 The strong and loose interconnections between the strategy themes and the competency themes based on the frequency of their co-occurrence

Institutional-level challenges

With institutional-level challenges of shortage of resources like funding, trained teachers, or enough class time, and lack of confidence and support of school boards, educators can find it particularly challenging to provide the much-needed time and personalized scaffolding to their students. AD points out,

> *"it's a lot harder [when] you're meeting kids one hour a week for 40 minutes and [with] program in schools that are underfunded. We're starting to focus more on [teacher] education and training, as opposed to curriculum delivering so that teachers can begin to do this themselves."*-[AD]

This makes it crucial for us to develop solutions for learning within makerspaces that align well with educators' priorities and mitigate the challenges.

Interconnected themes

We analyzed the co-occurrence of competencies and strategies in Fig. 6, which identifies all the times a competency (x-axis) co-occurs with the strategy (y-axis). By comparing the frequency of co-occurrence themes, we found that some themes had a stronger correlation than others. Figure 7 illustrates the interconnections between the themes. These findings provide the opportunity for further deep-dive analysis.

Scaffolding and learning technical skills

We observed that the strategy of scaffolding learning was most frequently cited in conjunction with learning about tools and processes. In particular, the scaffolding strategies co-occurred most often along with the learning of technical skills. Educators often discussed using project scoping, and progressive teaching of concepts for teaching disciplinary skills within making.

Encouraging failures and creative mindset

Another set of co-occurring themes were the strategy of encouraging failures and fostering a creative mindset. By allowing and encouraging learners to fail, educators were trying to make space for the learners to experiment, take risks, and think outside the box as they defined and scoped their problems. The ability to nurture a growth mindset, thus, was mutually linked to instructors' perception of their ability to foster creativity.

Fostering collaboration and communication skills

Similarly, fostering collaboration was cited most often with communication skills. By working together on projects, students are put in situations where they need to effectively communicate their ideas and negotiate with one another, developing crucial communication skills.

Building relationships and developing a sense of agency

Building positive relationships between educators and students, as well as among peers, was cited with the importance of learning to take agency. Educators noted the importance of creating a supportive environment through trust and engagement for students to take ownership of their learning and feel a sense of control over their education.

Differences in practices

In the previous sub-sections, we discussed how in spite of the differences within makerspaces in terms of their scale, class size, age groups, funding structure, and class frequencies, the educators have several similarities in their values, approaches, and experiences. However, we also observed some unique aspects associated with each of the makerspaces and differences among the educators' practices. For example, educators from the tuition-based full-time programs had a much stronger emphasis on learning a wide range of competencies compared to afterschool programs where the educators emphasized learning one or two competencies at a time. The educators in the full-time Novel school, for example, aimed for broad scoping so the students could explore a breadth of skills, while educators in Innovate afterschool preferred a much narrower scoped project for the students where they were exposed to learning fewer competencies during the course. We also observed that there was no uniform way among the educators to structure the competencies and integrate them into the curriculum. Every educator designed their activities ad hoc based on their teaching philosophies and experiences. This can lead to a variation in the experience of learning in makerspaces for the learners. While all our participants described personalizing support individually for students, only the tuition-based school could scale this approach due to the funding structure and available infrastructure. Conversely, part-time programs reduced problem scoping and project stages to make it more manageable, resulting in a more prescribed approach of learning.

These differences point to critical factors, such as the context of makerspaces and the resources provided to educators, that present both opportunities and challenges for designing educational HCI technologies. In the next section, we discuss how our findings can begin to inform the design of educational tools and technologies for makerspaces, particularly for further research in the HCI community.

Discussion

In this work, we set out to better understand how makerspace educators' perspectives could influence the design space of learning experiences and environments and we believe that our findings present particularly rich insights into opportunities to develop learning-oriented technology within makerspaces. In this section, we discuss them in the context of the broader Learning Sciences (LS), Computer-Supported Collaborative Learning (CSCL), and Human-Computer Interaction (HCI) literature.

Comprehensive support problem-to-project based scaffolding throughout all stages

Educators in our study stressed the importance of fostering higher-order problem-solving abilities that require merging knowledge across domains, tools, and materials to make informed decisions in open-ended contexts similar to real-world scenarios with diverse objectives and constraints. They also underscored the need for comprehensive support throughout all project stages, such as conceptualization, fabrication, testing, and iteration, rather than focusing solely on execution. This challenge intensifies when adapting project scopes and complexities to accommodate learners with diverse skill levels, all while aiming to sustain motivation and bolster learners' sense of agency.

Similar to our insights, research in Learning Sciences, like Barron et al. (2014)'s work on re-framing problem-based pedagogical approaches as project-based applications emphasized the need to study scaffolds for reflecting on conceptual knowledge and transfer across scenarios. To support such project-based learning which still remains challenging for educators to carry out (Aksela, 2019; Aldabbus, 2018), Peng et al. (2022)'s system, designed for coding, offers cognitive scaffolding across phases involving problem understanding, modular design, process design, coding, and evaluation/reflection. We imagine that a similar type of scaffolding could be applied to making tasks for reflecting on what kinds of materials and tools they may use after they've been guided to deconstruct their problems and examine the personal and societal contextualization. Importantly, the system considers educators' roles, often neglected in maker literature (Vossoughi and Bevan, 2014). Research into such technology-based scaffolds could help maker educators strike a balance between limiting project open-endedness due to time/resources and fostering meaningful student learning experiences.

Supporting learners' self-reflection & metacognition

Educators emphasized another dimension of open-ended projects that fostered learners' self-efficacy, agency, and self-driven learning, which is conventionally challenging to design for (San Juan and Murai, 2022). To address this challenge, educators' approach involved integrating learners' interests, personal and sociocultural contexts, normalizing iterative processes, and promoting learning through failure. While limited time and resources make this harder to accomplish, we suggest that technologies that support self-reflective and meta-cognitive processes could contribute in this context. Some recent work has explored such engagement of learners in fabrication tasks involving representations of themselves and their communities as part of scoped collaborative projects (Nation and Durán, 2019). Similarly, early work on leveraging Large Language models to support developing self-reflective processes points to ways in which technology could support learners' meta-cognitive practices within collaborative projects (Turakhia et al., 2022a). Furthermore, adapting scaffolding, that adapts to learners' specific needs has been identified as something that is particularly fruitful in the context of open-ended learning environments (Munshi et al., 2023). Our findings advocate for additional research along similar lines of technologies to facilitate educators in supporting learners' exploration and representation of their own identities and their communities within making tasks. We see this as an opportunity for both the makerspace literature and the learning sciences literature to come together to create knowledge where the collaborative nature is taken into consideration within the learning designs.

The Need for collaborative technology designs

When it comes to the collaborative aspect of learners engaging in group activities and projects, our educators developed pedagogical and spatial structures to support engagement across learners. They emphasized the importance of learners engaging closely with themselves as well as the other students. However, they also found that the students might disengage because of facing challenges working with one another on the technology. Existing learning and fabrication tools are typically not explicitly collaborative or designed with the presence of an educator in mind. This has resulted in researchers finding the importance of integrating multiple individual tools across the physical and digital space to support more inclusive collaboration by increasing opportunities for simultaneous engagement across them (Richard and Giri, 2019). Research has identified how simple overlooked factors, like the size and visibility of the fabrication tools, can impact opportunities for collaboration (DesPortes et al., 2016). Our findings call for design that focuses explicitly on collaborative learning approaches through increased interactivity, distributed control, knowledge exchange, and social interdependence among students engaged in shared-making processes.

Opportunities to support communication & criticality

In collaborative practices, educators stress the importance of learners communicating ideas verbally, in writing, and visually, and emphasize that learners teaching and critiquing each other fosters knowledge sharing and efficacy growth. They saw these social skills as essential for learners to improve their ideas, get comfortable engaging with a diversity of perspectives, weigh feedback to make decisions, and ultimately grow their efficacy as a maker. The work draws attention to a few directions technology can explore to support educators in these goals. This could include creating, navigating, consolidating, and sharing online resources for their learners. Second, it raises the question of supporting presentation and peer-teaching in group settings in equitable ways. Some recent advances in multimodal learning systems show promise in facilitating presentation skills (Ochoa, 2022) and group work (Lewis et al., 2023), which could prove promising if explored in the context of makerspace environments and project critique. The nature of these goals creates opportunities for connecting with arts education to develop critical thinking and communication skills, as it cultivates *habits of mind* (Sheridan et al., 2023) through *observing (not just looking)*, *divergent exploration*, *envisioning solutions*, *evaluating*, *finding meaning*, *questioning*, and *explaining* (Hetland et al., 2015; Sheridan et al., 2014, 2023). While these skills are often mentioned in the makerspace literature, there has been little work within interaction design exploring how technology might facilitate these types of practices.

Drawing attention to trust and care

Our educators also identified the importance and the challenge of developing interpersonal trust with learners as part of the experience. Their interviews highlighted the impact of these connections in supporting learners to engage in experimentation and exploration and to overcome self-doubt, failures, and project roadblocks. Prior work has advocated for attention to the ways in which *psychological safety* can be fostered within making activities through organizational supports and instructor dispositions that can facilitate trust and empathy in the learning environment (Desportes et al., 2022). Research needs to further investigate how we can develop these types of caring relationships (Noddings, 2012) within makerspaces to support learning in what can be an uncertain and failure-heavy environment.

Limitations and future work

We acknowledge that our study has several limitations and hence the findings of this work need to be tested further through more studies. Some of the limitations of our study include:

Small sample size & possible selection bias

The limited sample size of participants may not capture the full diversity of educators in makerspaces, including variations in experience, background, and teaching approaches. Furthermore, even though we followed purposeful sampling for selecting our interviewees, the participants were selected based on our networks, which could lead to a non-representative sample. We acknowledge these limitations and their impact on the ability to draw broader conclusions or make generalizations about educators' practices in makerspaces.

Subjectivity in the analysis & possible bias in coding

The subjectivity of interpreting data and identifying themes during the thematic analysis process can introduce biases into the coding. Different researchers may interpret the data differently, potentially leading to discrepancies in identifying and defining themes. Despite efforts to ensure interrater reliability agreement of 80% in each round, biases may still be present in the coding and analysis process.

Limited scope and context

Our study specifically focused on the pedagogical practices, and not on other important factors such as organizational structure, resource allocation, or community engagement. This limits our insights and a holistic understanding of the complexities involved in educators' practices in makerspaces. Finally, even though we diversified the types of makerspaces, the locations of our makerspaces primarily include the geographic region of the North American continent, which may limit our insights. Educational contexts vary across different locations, and the practices and challenges faced by educators in one setting may not necessarily apply to others.

This study is in no way exhaustive of the competencies, strategies, or challenges that maker educators might communicate. We aimed to provide an analysis of these educators' perspectives in order to shed light on the various avenues for design that are being left out. As a community, we must continue this investigation and iteration of educational maker technologies that integrate the perspectives, knowledge, and practices of all stakeholders, including educators. For future work, we plan to dive deeper into educators' strategies and challenges within diverse formats and contexts of makerspaces and how it impacts the learner's experiences.

Conclusion

The way educators understand learning opportunities is central to how they structure activities and thus central to how learning occurs in these spaces. Building this understanding of how educators scope and prioritize learning within their environments is central to how we design for learning and create more supportive learning environments that allow for effective pedagogical practices. To that end, we presented our work in this paper by studying the educators' perspectives and practices in makerspaces. Through a thematic analysis of the interviews of seven educators across five makerspaces, we identified the competencies, strategies, and challenges prevalent in makerspaces. We discussed how the findings of this study have important implications for the design of educational spaces, including makerspaces. We hope that by directing attention to the educators we can ensure that we have an eye towards equity through breaking away from notions of siloed learning experience, and as Vossoughi et al. (2016) state, pay "explicit attention to pedagogical philosophies and practices." This study serves as a starting point for further research in this area, and we hope that it will contribute to a greater understanding of the role of educators in makerspaces and the design of effective educational spaces.

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