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Enabling children's genuine participation in digital design and fabrication: instructors' perspective

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Abstract
Digital fabrication laboratories (Fab Labs) are accessible to the public, including children and families. However, a variety of technical skills, tools, and expertise are needed in these spaces, and Fab Lab staff—instructors working there—are in a key role in helping Fab Lab users. There is, however, a lack of research on how these instructors can inspire children's genuine participation in Fab Labs. We analyze the challenges faced by four instructors during two months of Fab Lab workshops with 7–12-year-old children. The children worked in child-only or child-parent groups on informal digital design and fabrication activities. Based on genuine participation principles derived from the literature, we designed our workshops, which included the creation of instructor guideline. At the end, we developed a post-workshop framework in which the instructors provided feedback about their performance and experiences. We provide recommendations to help instructors support children's genuine participation in digital design and fabrication.

Keywords Children · Digital design and fabrication · Fab Lab · Genuine participation · Instructor · Makerspace · Child-computer interaction · Facilitator

Introduction

Making has gained popularity in recent years. Central in the maker movement is that communities of people engage in the creative production of artefacts and share their thoughts and products both physically and digitally (Halverson & Sheridan, 2014). Makerspaces are an integral part of the maker movement. Fab Labs are an example of makerspaces. Fab Labs are a relatively new phenomenon in the design world, that are of high interests to several types of people, even those who are not designers (Atkinson, 2017). Around the world, Fab Labs are being built to make cutting-edge technology accessible to the general population to solve their problems and fulfil their needs (Stacey, 2014). Advanced physical computing and digital fabrication technologies available in these spaces open up endless possibilities for ordinary people to make, create, share, give, learn, play, and participate (Hatch, 2013); truly democratizing innovation (Gershenfeld, 2005). There are four

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essential characteristics of Fab Labs: accessibility, social inclusion, a sense of community, and collaboration (Roma et al., 2017). Open models of design, innovation and education are explored in Fab Labs (Kohtala, 2016). However, few empirical studies describe how Fab Labs are actually manifesting these ideals in practice (Kohtala, 2016).

Makerspaces and Fab Labs are providing a significant site for design, technology, computing and Science, Technology, Engineering and Mathematics (STEM) education – also for targeting children [see e.g., (Blikstein, 2014; Dindler et al., 2020; Fasso & Knight, 2020; Halverson & Sheridan, 2014; Kafai et al., 2014; Papavlasopoulou et al., 2017; Tuhkala et al., 2019)]. The process of making artifacts using computer-controlled fabrication techniques is often referred to as digital fabrication (Gershenfeld, 2012). Maker education can incorporate digital fabrication activities as a relevant context (Iwata et al., 2020) as digital technologies have a significant impact on the current maker culture (Martin, 2015). Digital fabrication is one of the tools that allows children to contribute to the design of the world. With the advent of digital fabrication, design and making have ceased to be distinct stages of the design process (Corsini & Moultrie, 2018). However, digital fabrication technologies are not widely adopted in K-12 art and design education (Song, 2020). Moreover, a broader recognition of design education is essential to the development of maker education (Lee & Kwon, 2022).

Maker education activities are typically learner-centered and open-ended do-it-yourself endeavors that entail engaging children in rapid prototyping and iterative cycles of trial and redesign, allowing for learning from failures (Blikstein, 2014; Smith et al., 2015). The educational framework is grounded in constructivism, a theoretical foundation that views learning as the process of constructing meaningful connections between existing knowledge and new information (Blikstein, 2014). Open-ended learning processes are commonly considered to be part of maker education, emphasizing students' own ideas and the power of learning by doing (Niiranen, 2021). However, it is important to note that children require support and guidance when engaging in making and digital fabrication activities (Norouzi et al., 2021b). In providing such support, maker pedagogy encourages educators to acknowledge not only their existing technical skill sets as technology teachers, but also their personal identities as individuals who actively create and engage with technology (Bullock & Sator, 2018).

Digital fabrication and making are introduced to children in different learning contexts, both formal and informal. It has been recognized that it is crucial to expand maker education policy to the public (Lee & Kwon, 2022). Makerspaces can be either non-formal learning spaces in schools, or informal learning sites outside of schools (Tan et al., 2021). In this study, we are in the pursuit of children's open-ended learning in an informal learning space of Fab Lab. There is plenty of research exploring the role of adults in introducing digital fabrication activities to children in various informal learning contexts (Tisza et al., 2020) such as in museums (Kazemitabaar et al., 2017) and libraries (Romero & Lille, 2017). However, oftentimes, these projects are adult initiated and driven. While they offer children valuable glimpses into the existence and potential of various technologies, children's genuine participation in digital design and fabrication is often lacking (Iivari & Kinnula, 2016). This comes as no surprise—while Fab Labs aim to share tools, skills, and knowledge, the barrier to entry for non-technical persons remains high (Dreessen, 2020). Collaboration in a Fab Lab is challenging and it requires a configuration of new forms of collaboration (Roma et al., 2017). Currently, it is largely up to Fab Lab instructors to manage participation of any Fab Lab visitors, whether they are adults or children. Even though instructors are mediating, facilitating, orchestrating, and scaffolding children's learning in valuable ways (Dreessen & Schepers, 2018; Norouzi et al., 2021b) they still have varying backgrounds and training. While they often have strong background in technology or engineering, or alternatively, in educational sciences (Milara et al., 2020), their expertise in facilitating truly learner-centered, open ended DIY projects with children, entailing children's (genuine) participation, can be very limited. The aim of this qualitative study is to examine: '*what are the challenges instructors face in an open-ended informal Fab Lab setting when attempting to instruct children in activities set up to allow children's genuine participation*? *How can instructors' work be supported*?'.

Related research

Digital design and fabrication with children in informal open-ended setting

The context of this study is the informal Fab Lab learning environment. According to Eshach (2007), informal learning can happen everywhere; it is supportive, unstructured, non-sequential, spontaneous, voluntary, and usually learner-led; motivation is mainly intrinsic, and learning is not evaluated. Currently, maker education is primarily conducted with students in K–12 schools; however, it should take place both inside and outside of schools in order to spread the maker culture. For the maker education to succeed and to take full advantage of the many resources available, linking local communities to the maker education is essential—not just students, but also parents, ordinary people, and the elderly. Different activities should be conducted with people from different fields using the makerspace in each community. (Lee & Kwon, 2022). Prior research has already addressed children's informal (and non-formal) learning in makerspaces located, for example, in museums, libraries, and Fab Labs, in which children have participated during their leisure time, the activities ranging from open-ended to more structured hands-on experiences [e.g. (Chu et al., 2015; Fitton et al., 2015; Norouzi et al., 2021a)].

We identify a challenge in informal learning settings in balancing between structure and guidance versus free choice learning and exploration. In informal learning settings, students have more autonomy, as they can set their own learning goals, which gives them a greater sense of ownership of their learning (Tan et al., 2021). Free-choice learning refers to a learning approach h where learners have autonomy in choosing what, where, how, and with whom they learn (Falk et al., 2007). Typically, free-choice learning is characterized by high intrinsic motivation, as learners are motivated to explore topics of their own choice (Falk et al., 2007). While motivation plays a significant role in achieving learning gains, enabling it remains one of the major challenges in open learning environments (Salmi & Thuneberg, 2019). This type of learning often occurs in informal settings outside of traditional school hours and has been shown to have several positive outcomes. For instance, free-choice learning can inspire and retain pupils in STEM fields (Falk & Storksdieck, 2009), enhance their understanding of science beyond the classroom, improve student engagement, and foster a sense of ownership in their learning (Drissner et al., 2014). Moreover, participation in such experiences has been linked to increased academic performance (Arya & Maul, 2012). For instance, the findings from a study conducted in a mathematics classroom reveal that when students view themselves as active participants in the learning process rather than passive recipients of information, it positively impacts the classroom environment and sustains their interest in mathematics (Mitchell, 1993).

However, to foster active engagement, student-centered teaching approaches should provide clear instructional guidance and structure that takes into consideration students' perceptions and incorporates them effectively (Dochy et al., 2011). Drawing from prior empirical research, it has been observed that novice pupils tend to benefit less from minimally guided instructions, compared to instructional approaches that prioritize direct guidance on the learning processes in terms of both effectiveness and efficiency (Kirschner et al., 2010). Providing students with direct instructions has been shown to facilitate deep learning, enhance their ability to recall information, and enable them to transfer knowledge effectively to solve novel problems (Mayer, 2004). Guiding the cognitive processing of novice students, including activities such as selecting, organizing, and integrating knowledge, not only impacts their current learning outcomes but also has a positive influence on the development of their problem-solving skills (Mayer, 2004). Furthermore, adhering strictly to pre-designed plans may not be conducive to motivating learners (Schelhowe, 2014). The most effective out-of-school learning experiences might be those with intermediate levels of structuring while still allowing free exploration (Gutwill & Allen, 2012). However, striking the right balance between nurturing students' imagination and creativity, while also setting appropriate boundaries to guide their progress, is a complex task that requires careful consideration (Carrington et al., 2015).

In the literature on digital design and fabrication with children, the importance of open ended and free exploration has been underscored. Studies have emphasized open exploration in digital fabrication (Bekker et al., 2015) and digital design (Mohr et al., 2016), and iterative problem solving, shared meaning making, and teamwork as valuable learning opportunities (Sinervo et al., 2021), and an element contributing to genuine participation of children (Kinnula & Iivari, 2019) and children's capability in envisioning and pursuing their own projects (Sheridan et al., 2019). Reduced open-endedness can significantly clash with the making philosophy and the relationship between made objects and personal relevance can suffer due to it (Fasso & Knight, 2020). However, as we will show in our study, there are many dilemmas Fab Lab instructors encounter when facilitating these open-ended learning activities with children.

Adults' roles in digital design and fabrication with children

There is existing literature on adults' roles in children's digital design and fabrication activities. Prior research on adults' roles in children's design and making activities in the context of Fab Lab (Norouzi et al., 2021b) finds adult actors as mediators of children's learning by facilitating learning (providing children with technical support), encouraging learning (emotional and social support), and orchestrating learning (children's behavioral management). In design activities with children, the roles of a playmate and a friend for adults are also introduced (Dreessen & Schepers, 2018). Further, with children with special educational needs, five roles for adults are identified: facilitators, motivators, caregivers, proxies, and co-designers/design partners (Benton & Johnson, 2015).

A lot of the literature on adults' roles addresses teachers as non-specialists in digital fabrication. Developing effective ways for teachers to understand and use digital fabrication technologies in K-12 classrooms is seen essential (Song, 2020). To be successful in project-based learning, teachers must gain technology knowledge and skills, as well as establish interdisciplinary connections (Fan, 2022). Despite the autonomy advocated by the maker movement, teachers still need to demonstrate various processes and techniques (Nemorin, 2017). Guidance from teachers is crucial to the successful pursuit of co-invention (Sinervo et al., 2021). However, typically, teachers have limited time to refine their digital competences (Tenhovirta et al., 2022). It is common for teachers not to be routine experts in digital fabrication, as they lack adequate design education and experience (Christensen et al., 2019). In a study, teachers ranked their own core competencies lower than they rated their importance (Fan, 2022). Although digital design itself is not a new phenomenon, there is little knowledge about what teachers intend pupils to learn from digital design involving computer-aided design (CAD), as teaching involving CAD is a relatively new element in compulsory and lower secondary technology education (Brink et al., 2022). Here, our focus is on digital design involving CAD for digital fabrication, where the input to the machine/fabrication equipment is digital data in the form of a CAD file and the output is the product made by the machine.

There is also literature discussing the perspectives of involved adults and challenges they face in informal learning environments (Litts, 2015; Roque & Jain, 2018; Tisza et al., 2019). A supportive and productive learning environment involves scaffolding with exemplar artifacts and social, emotional, and technical support from peers and facilitators. Facilitators play an important role in supporting social engagement of the participants (Fasso & Knight, 2020). Moreover, peer tutoring provides significant support for implementing Science, Technology, Engineering and Mathematics (STEAM) education and making practices; however, tutors would need a variety of pedagogical, social, and technological skills (Tenhovirta et al., 2022). In terms of children's engagement in longer-term trajectories, adults who take the time to organize backstage activities are shown to be effective in opening up learning opportunities (Dreessen & Schepers, 2019). Despite this, the role of adults is somewhat overlooked in the arrangement of activities, as the emphasis is on front stage activities (Dreessen & Schepers, 2018), ignoring the impact of backstage activities on establishing appropriate authority and influencing the roles played on stage (Barendregt et al., 2018). Moreover, there is little discussion about the adult actors' interactions and challenges in digital design and fabrication with children (Norouzi et al., 2019). In our study, we examine how Fab Lab instructors can be supported both in frontstage and backstage activities to enhance children's participation in digital design and fabrication.

Theoretical lens: conditions of genuine participation

We acknowledge that the literature on maker education emphasizes important maker culture values to be respected and realized by the instructors working with children while we also acknowledge there are challenges and dilemmas in achieving these values. Additionally, to be able to guide and scrutinize in detail the work instructors do in trying to realize children's learning in a child driven, open, DIY manner, we take inspiration from literature discussing ideals of genuine participation of children by Kinnula and Iivari (2019) which strongly argues for meaningful and effective participation of children in all matters affecting their life. Kinnula and Iivari (2019) build upon the established multidisciplinary literature base on children's genuine participation, empowerment of children and the principles of Scandinavian participatory design (Druin, 2002; Iversen et al., 2017), and propose a four-part genuine participation framework to understand how children and other user groups can genuinely participate in technology design and making.

This study is based on the second part of the framework (Kinnula & Iivari, 2019), which is based on work by Chawla and Heft on conditions that allow meaningful and impactful participation of children (Chawla & Heft, 2002). This work aligns well with as well as strengthens several aspects underscored in maker education, providing structure for analysis of these aspects. The five sets of conditions for children's genuine participation include conditions of: *convergence*, that underscore the significance of building the work on the existing, supportive structures and processes as well as on the interests of the participants; *entry*, that highlight the inclusive, voluntary, and accessible nature of the work; *social support*, that emphasize respect for human dignity as well as collaboration and encouragement; *reflection*, that consider transparency and negotiation of power differences and decision-making as well as critical reflection on the process and outcomes; and *competence* that address responsibility and impact, competence development, and informed decision-making.

This second part of the framework provides a method for comprehensively assessing the project in which children engaged in the Fab Lab environment and the instructors' role within. The framework can overall used to critically evaluate projects that involve many participants, including children and families, during and after the projects. The framework can also be employed in designing and planning projects for ensuring that participation is meaningful and impactful.

Research design

Our qualitative research following the interpretive paradigm (Denzin & Lincoln, 2000; Klein & Myers, 1999) aims to focus on the meanings attached to the phenomena under investigation: instructors' perspectives in enabling children's genuine participation in digital design and fabrication. The framework introduced by Kinnula and Iivari (2019) combines theoretical insights from existing literature on nexus analysis, values, value, empowerment, and genuine participation of children. Particularly, we relied on the research strategy of nexus analysis (Scollon & Scollon, 2004) which entails cycles of engaging, navigating, and changing the nexus of practice. Engaging refers to researchers becoming familiar to the community being researched, while navigation entails collection and analysis of various kinds of data to answer the research questions. Changing, in line with nexus analysis, is seen to feature any qualitative, participatory study, while it can also be intentionally aimed at in collaboration with the study participants to address a social issue or problem (Scollon & Scollon, 2004). Translated into the context of this study, the cycle of engaging was initiated years ago, when the researchers became familiar with the Fab Lab and its instructors. Navigation entails the data collection and analysis reported in this study, while changing was an integral element of this study: we pursued towards more genuine participation of children in collaboration with the instructors, relying on the framework of genuine participation of children.

Our project in the Fab Lab included a series of workshops, in collaboration with a local city Fab Lab. We addressed the conditions of entry for children's genuine participation (Kinnula & Iivari, 2019) where fair selection of the participants, voluntary participation, flexible schedule, and accessible location are highlighted factors. To recruit children, a flyer was designed and distributed via the international university, children's school, and local Fab Lab channels. There were 17 participants in total, 12 of whom were children between the ages of seven and 12. Five family groups of five parents, aged 35–42, and their six children (two were siblings), and two child-only-groups formed of six children participated in the workshops. A total of four researchers observed the sessions, with usually three of them present in any one session. Figure 1 shows some of the groups' activities and made products during the Fab Lab workshops.

Fig. 1 Some examples of the groups' activities: (top-left) performing some electronics work on a 3D printed robot, (top-middle) laser cut wooden jewelry set, (top-right) a doll house made with 3D printed and laser cut parts, (bottom-left) adding some light to a guinea pig house made with laser cut wooden parts, (bottom-middle) a child working with micro: bit, (bottom-right) testing a flying boat with a body laser cut from wood

The instructors

In the informal Fab Lab context, an instructor is one of the main actors who interacts directly with Fab Lab visitors to help them with their projects. Therefore, Fab Lab instructors play an influential role in (genuine) participation of children. In planning the workshops, we aimed at advocating the genuine participation of children through the work of the instructors. To achieve this, we focused on the conditions of convergence, social support, reflection, and competence[1] (Chawla & Heft, 2002) as well as empowerment of children in and through digital technology design (Kinnula & Iivari, 2019). Considering these theories, we drafted simple guidelines for the Fab Lab instructors to use when working with children. Figure 2 depicts the formation of the instructor's guidelines. And Fig. 3 represents the items of the instructor's guidelines. We suggested they consider the points in the guidelines when instructing the workshop participants. Apart from that, they were free to guide children according to their own style, as they usually instruct Fab Lab visitors. Four instructors with diverse cultural backgrounds volunteered to instruct the participants. They were all FabAcademy[2] graduates as well as part-time or full-time Fab Lab instructors. All the instructors were familiar with the maker education principles including hands-on-learning, creativity and innovation, open-ended exploration, collaboration and sharing,

[1] The conditions of entry were not included as the instructors were not involved in this stage of work.

[2] FabAcademy is a 6-months distributed-learning course, taught yearly, where participants from more than 80 Fab Labs all around the world learn to utilize the main digital fabrication tools and processes.

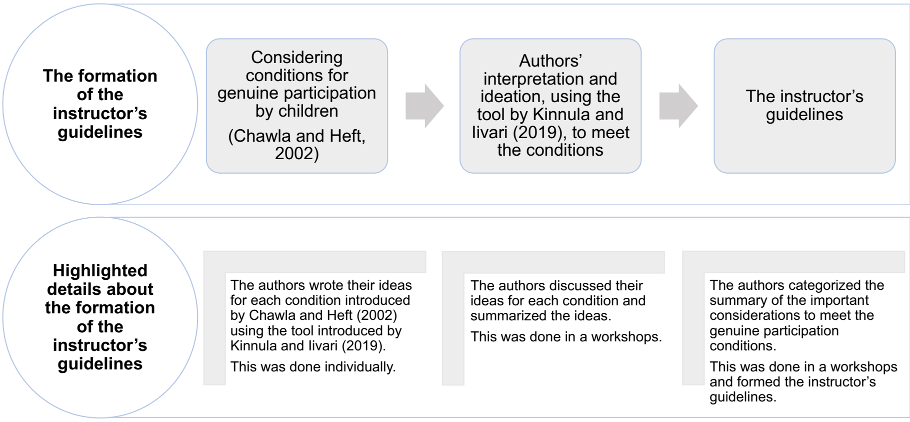

Fig. 2 The formation of the instructor's guidelines

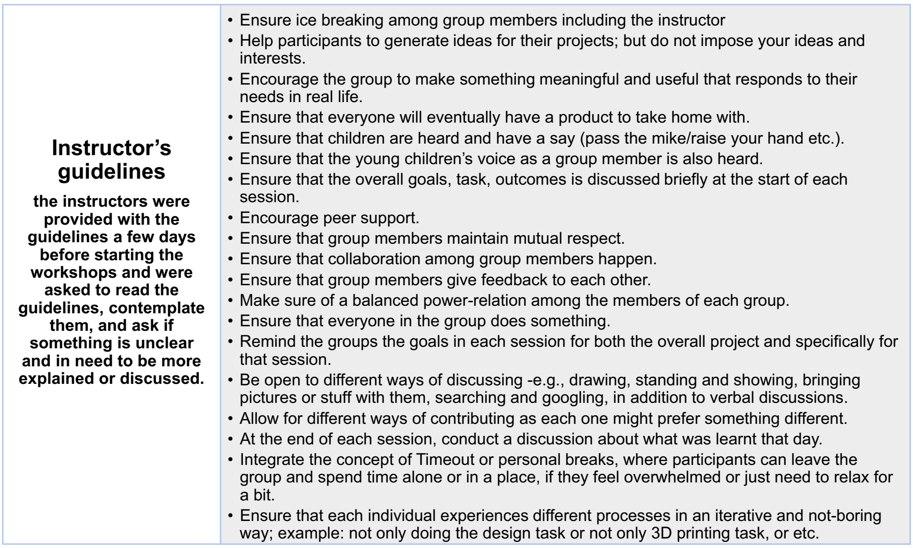

Fig. 3 The items of the instructor's guidelines

Table 1 The instructors

Participant	Gender	Age	Academic background	Prior experiences working with children in a Fab Lab
Instructor 1	Man	28	Radio physics	No
Instructor 2	Man	42	Embedded systems	No
Instructor 3	Man	39	Telecommunication	Yes: short, structured workshops
Instructor 4	Woman	32	Education	Yes: short, structured workshops

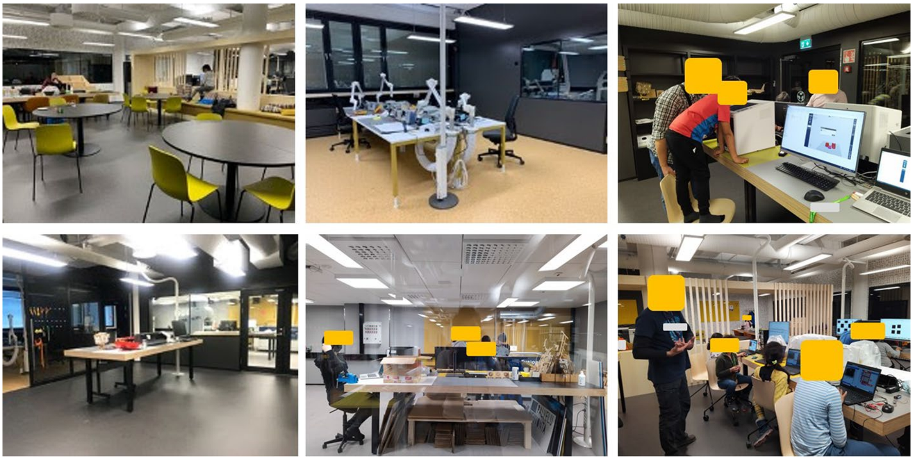

Fig. 4 Fab Lab spaces: (top-left) an open space with round tables and chairs used to group discussions and ideation sessions as well as for breaks and snacks, (top-middle) an electronics workstation with soldering equipment, (top-right) 3D printing workstation, (bottom-left) standing table with a vinyl cutter behind which (bottom-middle) is a large closed-room with a laser cutter, and (bottom-right) is computer workstation with two tables, the front one with laptops on it for child-group work and the other one with computers on it for families' group work

critical thinking and problem solving, inquiry-based learning, and reflection and iteration. Table 1 presents some details of the instructors. Instructor 4 was a substitute instructor.

Fab Lab activities and space

28 workshops were scheduled: two by 14 two-hour workshops: 14 workshops on Monday & Thursday (six participants; two family groups (four members) & one child-only (two members) group) and 14 workshops on Tuesday & Friday [11 participants; three family groups (seven members) & one child-only group (four members)]. The participants engaged in different digital design and fabrication activities including 2D/3D modelling, laser cutting, 3D printing, vinyl cutting, microcontroller programming, and electronics production along with some traditional making activities such as paper-drawing, Play-Doh, and cardboard prototyping. The normal way of working in a Fab Lab was adopted: 'do-it-yourself and help will be provided by instructors when needed.' The instructors gave short introductions to the main processes and supported the children and families by showing them how to use the software and machines whenever needed. Figure 4 shows the Fab Lab spaces.

Data collection and analysis

The informed consent form contained information about the researchers and their goals, means of data collection, and handling, storing, and utilizing the research material as well as personal data according to General Data Protection Regulation (GDPR) Article 6(1): participant consent. All the participants were given the right to withdraw from the study at any point. Assent was obtained from the children, and consent from their parents and instructors.

After the workshops, a post-workshop feedback form was prepared to address the instructors' experiences through the lens of the genuine participation framework (Chawla & Heft, 2002; Kinnula & Iivari, 2019) that was also used for planning the workshops. The form comprised seven sections: context, values, convergence, social support, reflection, competence, and utilization of the instructor guideline. The instructors filled in the online evaluation form individually over the course of one week.

For the data analysis, first, three researchers mapped the instructors' responses to the genuine participation framework, which included conditions of convergence (context affecting the activities; easy and natural participation for the participants; basing the activities on children's own issues and interests); social support (supportive environment; mutual respect and valuing all opinions; frustrations, stressful situations, and conflicts); reflection (reflecting on the power dynamics and decision-making in the groups; reflecting and discussing within the group during the workshops); and competence (goals of the activities; impacts of children's activities; supporting learning and independent initiating of future projects). Second, those researchers utilized thematic analysis (Braun & Clarke, 2006) to categorize the mapped data for each genuine participation condition. Lastly, together with two senior researchers who were involved in the wider project collaboration, five researchers collaboratively analyzed and agreed on the categorization in a hybrid data analysis workshop. In the next section, findings from the data analysis are presented for the conditions of genuine participation analyzed in this paper.

Findings

Next, we introduce our findings from the instructors' perspective on the conditions of convergence, social support, reflection, and competence. By participants, we refer to the workshop groups, both children and families. From a genuine participation perspective, children's participation is naturally in the focus, as our aim is to nurture children's agency in their everyday lives, that is, empowering children to affect and impact their own decision-making and experiences.

Conditions of convergence

Context affecting the activities

The chosen context for this study was 'open-ended informal afterschool Fab Lab activity'. Two instructors mentioned that although these types of activities in such a context should not be completely structured, giving freedom to the participants to make anything they wish, is too ambiguous and confusing for children, especially for the younger ones. They argued that children might achieve better results if they are provided with semi-structured activities in the form of concrete projects. In line with this belief, an instructor tried to introduce material of the day for a session with a concrete example of a Halloween theme. This approach, however, did not work as none of the children showed interest in the theme when they had the option of choosing their own products. Two other instructors believed that structured activities might be boring for the participants and that the setting of the study reflected the typical working process of a Fab Lab and helped in building interest in the process, boosted participants' creativity, and developed their understanding of digital manufacturing.

The most highlighted concern was related to how to structure these types of informal Fab Lab activities. The workshop high-level design, which aimed at enabling genuine participation of children, affected interaction between the children, families, and instructors as well as the instructors' instructing methods, where instructors sometimes had to overlook their values originating from their personal experiences and backgrounds. Two instructors were confused about the extent to which they could include structured instructions (which they preferred), as they were asked to respect children's ideas and assist children in turning ideas into working prototypes. This clash in values introduced a state of uncertainty and internal conflict for them. However, two instructors saw no conflicts between their own and researchers' or participants' values; "*I didn't have expectations. Because of the lack of experience in the workshop area. It was no pressure for me*". Nevertheless, based on their experiences and the challenges they faced, they both mentioned they might appreciate some structure in the activities.

Easy and natural participation

The major benefit of the context for the instructors was their own familiarity with the Fab Lab and its practices, given their training as Fab Lab instructors; "*It didn't differ much from normal guidance given for everyday visitors, except that child needed to be reminded what they were doing*". One instructor mentioned liking the informal nature of the activities while another found that to be challenging and in conflict with [their][3] expectations.; "*Well, it was fairly easy. I had great groups of students and there was not so much pressure due to the informal format of the activity.*", and "*It was easy because of the similar context with the daily work at the Fab Lab. But I was feeling some kind of pressure that the kids should get something done in the limited time (…) I did not put the value above in the facilitation of the sessions so much (…) To consider my current knowledge in digital fabrication, I am more comfortable in running workshops that I could take more control over what would happen.*" Guiding children-only groups or intergenerational child-parent groups was new for all instructors. Those who had previously worked with children had done so in the context of schools with the presence of teachers, who usually managed the children. According to two instructors, the supportive parental role within the family groups was beneficial for the instructors. An instructor was concerned that the families' participation was not natural, as this was their first time learning together in a Fab Lab. The instructors needed some time to figure out natural roles for themselves in interacting with each group; "*I spent some time trying to understand my role in every group but basically had three groups and it was a bit harsh*". Meanwhile, the instructors were inspired by each other's methods and ways of doing things.

Basing the activities on children's own issues and interests

The instructors talked with the participants to locate their interests, to base group-projects on children's ideas and interests. Generally, the participants had difficulties in coming up with viable ideas. An open-ended activity and participants' unfamiliarity with the working processes in Fab Lab sometimes hindered children from choosing the topic for their

[3] [they], [their], [them]: gender neutral terminology in square brackets is used for the purpose of anonymizing the instructors.

group project, which not only slowed the instructor down in instructing, but also increased the instructors' responsibility to provide excessive assistance; "*I spent some time trying to understand my role in every group but basically had three groups and it was a bit harsh*". Furthermore, the open format sometimes resulted in children proposing complex project ideas, which led to some challenges for the instructors, such as a need for saying no to the ideas, preforming parts of the projects for the children, helping children to figure out the ideas, and structuring the activity by designing an example project for the children.

Regarding methods for generating meaningful ideas, one instructor found it useful to start with a get-to-know-you activity, asking the children about their favorite games, books, TV shows, etc., and incorporating that information into the common theme of a low fidelity robot for the whole group to use. Two instructors found it useful to run short tutorials on designing, laser cutting, and 3D printing to help participants get familiar with the working processes and consequently to come up with meaningful ideas. Moreover, the instructors introduced some online tools and design repositories to help participants find ready models to ease their learning curve and incorporate ideas from those into their own group projects. One instructor tried to introduce different working processes to the children and let them experience different forms of digital fabrication through short activities, and then employed a 'bag-of-things' technique by offering multiple objects and combining them to generate more complex ideas. These techniques were not entirely successful as the children's ideas were still too complex to implement by themselves.

Conditions of social support

Supportive environment

The instructors felt that the atmosphere was supportive enough and the interactions among children, instructors, parents, and researchers were mostly relaxed, informal, positive, and friendly; "*I spent some time trying to understand my role in every group but basically had three groups and it was a bit harsh*". It was mentioned by an instructor that relaxed interactions had created a comfortable atmosphere for everyone. The children seemed to perceive learning in an informal environment as a fun leisure activity, even though handling children's distractions was a challenge. This challenge was attributed to a lack of clear rules, according to an instructor. In addition, the instructors spending time explaining something to one child or a family group often led to the frustration of other participants. Lastly, the instructors agreed that the number of instructors was limited for this type of activity, which became critical at times, such as when the groups became "*stuck and could not move without the instructors' guidance*."

Mutual respect and valuing others' opinions

In terms of the interactions between the instructors and the groups, the instructors' values manifested in respecting groups' ideas, bringing a friendly and kind atmosphere, and keeping children interested. When it came to learning, the instructors emphasized children trying new things on their own without being afraid, as well as maintaining an engaging and fun learning experience. As a result, the instructors ignored some parents' expectations that the instructors should be stricter towards the children to engage them; "*I did not want kids to see me as a teacher, but more like a person who is helping them to discover what can be done in Fab Lab*".

'Respect', according to an instructor, was about respecting children's needs as individuals who need to play, take breaks, and have fun while at the same time respecting each other. Another instructor maintained mutual respect by providing equal help to all participants. One instructor believed mutual respect was in the way children contributed to the group project, such as by asking an older child to give a chance to a younger child's ideas.

As the workshop was aimed at children, the instructors respected the importance of their voices. However, some instructors believed that it was the parents' duty to ask and verbalize their children's wishes. The instructors stressed that they listened to everyone's opinions, although this sometimes ceased due to the parents' intervention. Despite the efforts of the family members to support each other, there were some parents who took over because regardless of how much the children were involved in the discussions and activities, they constantly lost concentration; "*despite the fact that the children were involved in the discussion of the final project and they were told what and when we were going to do, it was difficult for them to maintain concentration and interest in what was happening*".

Conditions of reflection

Power dynamics and decision-making

The instructors were also asked to reflect on the power dynamics with the groups and on how decisions were made. From the offset it was understood that the instructors are responsible for organizing the activities in the Fab Lab sessions for their assigned groups. As one instructor noted, children in [country] are used to after-school activities and it was easy to manage and monitor participants as they expected to be instructed. However, for the instructors, it was important to differentiate themselves from teachers in a classroom and be less authoritative when guiding the children. The instructors helped the groups with the definition of the tasks of the day, using the tools and machines, facilitating the work dynamics, and assisting with ideation; "*[another] task of the instructor in this type of context is to channel the ideas and likes of the kids into some activities/output that kids would like*". The instructors also encouraged children to collaborate, guide, and support each other. One instructor asked children to take on the role of a teacher, but this was not always successful, especially when other children did not listen to the child who was the teacher. The parents also added many challenges to these complex social dynamics of instructor-child interactions. To these complex social dynamics of instructor-child interactions, parents also added many challenges. For instance, one instructor mentioned how a "*child felt [their] mother's decision*" overruled child's own because of their "*inability to choose a project, or the mother's impatience for waiting for an answer*". Another instructor reflected that "at some point in all cases parents took the lead role in the final project, but they tried to involve children as much as possible". The complicated parent–child dynamics also affected decision-making in the groups, which was worrying for the instructors trying to involve the children in all activities and in taking ownership of group-projects, which was not always successful.

In cases where the instructors tried to give the lead to a child, for example by asking them for their suggestions for a project, the children either had no answer or the suggestions were unworkable. The instructors gently guided the children into the realms of what is feasible in the Fab Lab when children's autonomy was not questioned or overruled by their parents. Furthermore, the instructors had to make decisions regarding the digital fabrication processes, such as what machine to use, how, and when, as the children did not have enough experience to decide such things by themselves. One instructor mentioned, "*I explained why we did something or why we did not go to the other task e.g., we do not use this machine yet because we are not prepared*"; this sometimes led to small complaints by the children eager to try a new machine or activity. Thus oftentimes, the instructors guided the children and parents by sharing decision-making power with both parties, especially when the task was technical or there were technical issues and limitations. The parents, however, were more involved when there practical and technical issues were discussed. Although the instructors attempted to explain their decisions in detail, they were not certain if their reasoning was understandable for the children; "*I tried to explain but [they are] not sure if [participants] fully understand the reason*".

Reflecting and discussing within the group during the workshops

During the workshops, instructors discussed the day's activities and challenges within their groups to take stock of the participants' progress and identify the challenges faced; however, the frequency and depth of these discussions varied between the groups. One instructor mentioned how [they] usually have reflection sessions in [their] work as a Fab Lab instructor with young people, but in these workshops, they had shorter discussions and that too not every session. Several reasons were given for this change, including limited time for completing group-projects and the children being too young for proper reflection. These discussions included asking "*what [the group] did today, and what are the next activities*''. In some cases, they also evaluated "*if the output is what [participants] expected or not and if it was easy or difficult*".

In all groups, instructors and participants discussed alternative design and technical solutions when things did not go as planned or when the instructors believed some ideas were not feasible. One instructor, whose group selected complicated project—to build a robot from scratch—utilized group reflections to collaboratively "*reflect on…what is worth the time and what is not*". At the end of each session, this instructor asked the group what the group learned and what the group enjoyed. In this way, the instructor evaluated the progress of the projects, ensured the group had something to present for the session, and facilitated a smooth transition to the next activity. Another instructor planned discussions for the start of the sessions, asking [their] group what the plans for the day were. As [their] group was divided into smaller subgroups (based on families), [they] did not emphasize collaboration between these subgroups as there was no collaboration among the different family groups.

Conditions of competence

Goals of the activities and their outcomes

The instructors mostly understood the purpose of the activities, but sometimes there was confusion about what the researchers expected from them as instructors. Some instructors used to set goals and plans for themselves and their groups before each session. The goals, however, were unclear for some specific cases; for example, for the substitute instructor who came to assist midway through the activities. The instructors reported that the groups were primarily responsible for coming up with ideas and timing as well as completing their group-projects, while the instructors believed their responsibilities included technical support and preparing activities to convey a simple and understandable explanation of the digital fabrication processes to encourage participants to learn new things.

To ensure tangible outcomes, sometimes the instructors aimed for small artifacts and simple semi-structured activities. During laser cutting and 3D printing of tiny toys, children's activities had the most visible impact. There were instances when group-projects were not completed by the participants. In other cases, the final products were a direct reflection of the children's efforts or included personalization and customizations that they had created; "*after many sessions, they were able to get something designed by them. For the final projects, they at least customized some parts as they liked*."

Supporting learning and independent initiating of future projects

All the instructors agreed that the children learned something useful about digital fabrication, especially those children who had clear actionable initial ideas. For example, some groups managed to use basic functions of 2D/3D digital programs; some learned how to control a motor or a light with a microcontroller; soldering; or operating a laser cutter. According to most instructors there is a need to clarify the extent to which children need to understand different types of software and machines; "*I don't think it's necessary, especially [for] small kids, that they understand what is exactly vectorizing […] But I think the idea [is] that you can take an image from the internet and put it in the program, make one operation and then cut it*". Furthermore, an instructor found that children learned more efficiently when [their] approach to teaching resembled activities that were familiar to children, such as teaching vinyl and laser cutting by using scissors or teaching 3D printing by modelling with Play-Doh.

All instructors agreed that what the children experienced during the workshop was adequate to give them an idea of what can be done with Fab Lab equipment, although some expressed that this amount of experience might not be sufficient to enable children to initiate activities independently without receiving support, and that many children would still need scaffolding in activities; "*I don't think it's necessary, especially [for] small kids, that they understand what is exactly vectorizing […] But I think the idea [is] that you can take an image from the internet and put it in the program, make one operation and then cut it*".

Discussion

Research has shown the value of making and makerspaces (Atkinson, 2017; Kohtala, 2016; Roma et al., 2017) while questioned children's engagement within those, recognizing the role of adults as well [e.g., (Dreessen & Schepers, 2018; Iivari & Kinnula, 2018; Iversen et al., 2018)]. So far, little attention has been paid to how we can better support adults in enabling children's genuine participation in digital design and fabrication, i.e., asking what kind of support the adults need, particularly in informal learning settings where children's own interests and motivations are in focus.

Prior literature has pointed out that the instructors' ability to support digital design and fabrication is limited by their own maker identities, so extending the instructors' identities by sharing best practices for making and learning among colleagues is essential (Litts, 2015). Our study shows that supporting children's genuine participation was not a straightforward task for the instructors to accomplish. Our instructors had varying experiences as Fab Lab instructors, diverse backgrounds, and varying comfort levels regarding working with children (in line with the existing literature, e.g., Milara et al., 2020; Norouzi et al., 2019, 2021b; Pitkänen et al., 2019)). Their expectations from the researchers for the information, material, and support, their use of the guidelines, and their experience with non-structured learning also varied. All of these affected their practical activities, challenges, and solutions. Further, it is recommended to facilitate rather than train facilitators, which can be achieved by enhancing collaborations not only between researchers and facilitators/instructors, but also among instructors themselves (Roque & Jain, 2018).

Structure of informal open-ended learning activities in a central role

According to our study, many practical challenges can be encountered on the way to children's increased agency in digital design and fabrication. We identified structure of the learning activities as one central issue that needs consideration. Open exploration in digital fabrication (Bekker et al., 2015) and digital design (Mohr et al., 2016) is considered to contribute to children's agency (Kinnula & Iivari, 2019) and capability in envisioning and pursuing their own projects (Sheridan et al., 2019). Our workshops aimed for children's open exploration and freedom in deciding what to make in an informal context because we see it as a key to children's intrinsic motivation (Deci & Ryan, 1985) and is in line with the making philosophy and Fab Lab working model. However, it came with challenges. Informal context entails unstructured activities while the activities in a non-formal context are structured (Eshach, 2007). Our research suggests that semi-structured activities might work better in Fab Lab environment. The environment is generally not the most child-friendly [see e.g., (Norouzi et al., 2021a)], which sets challenges for unstructured, child-led ways of working. Feasibility of children's ideas have to be also evaluated by the instructors, along with evaluating children's skills and abilities, and too open-ended and unstructured way of working can be challenging for the instructors due to various unpredictable factors (what are children's skill levels, what they want to do, how complex that is to implement, how long it takes, etc.). Instructors, especially novices in working with children, are unable to predict how much time and how easy or difficult it will be for children to implement the idea, when ideas develop based on children's interests. Besides, the instructors might lack knowledge or experience about techniques that facilitate idea generation, such as for instance, the bag-of-things technique (Yip et al., 2013). And as our findings suggest, these idea generation techniques might not even be useful when it comes to digital fabrication. For children's intrinsic motivation, they should be asked about their wishes and interests before beginning the activity, and these should be incorporated into semi-structured project themes and examples that instructors can create. This aligns with the general idea of Just-in-Time Teaching [see e.g. (Marrs & Novak, 2004)], where student pre-work is used as a feedback loop to tailor the contents in the classroom to support more active learning and engagement.

Classroom structures including task, authority, and evaluation are interrelated, and they influence instructional strategies and student motivation (Ames, 1992). Moreover, interventions that focus on changing or modifying these structures may yield varying outcomes for students, depending on their individual past experiences and meaning they give to their current experiences (Ames, 1992). To encourage active engagement, student-centered teaching methods should include clear instructional guidance and structured activities that consider and incorporate students' perspectives (Dochy et al., 2011). Greater levels of student autonomy are positively correlated with increased intrinsic motivation towards learning science (Salmi & Thuneberg, 2019). This way of working, in addition to aligning the overall theme of children's project with their interests, provides still ample room for creativity and individualization as the project is semi-structured. Furthermore, instructors may feel more relaxed and confident as they are able to teach basic skills to children rather than being stressed about providing extensive and excessive help due to the unpredictability of open-ended projects. Moreover, instead of teaching the same topics separately to different participants, this method should facilitate simultaneous teaching of the topics to a greater number of participants with different projects but requiring the same basic skills to complete them. In informal learning settings, it is crucial to strike a balance between structure and open exploration (Chen et al., 2022; Gutwill & Allen, 2012). By keeping this balance, explorations are likely to be the most effective (Gutwill & Allen, 2012) and intrinsic motivation would be sustained (Chen et al., 2022). Nonetheless, while motivation is a role player in learning gains, enabling it can be a difficult challenge in open learning environments (Salmi & Thuneberg, 2019).

Recommendations for enabling children's genuine participation in digital design and fabrication

In informal Fab Lab contexts, instructors play a primary role in increasing this agency and enabling children's genuine participation. Next, we provide some insights on how instructors can be supported to foster children's—as well as more generally learners'—genuine participation. Structuring of the activities is linked with many of these issues.

Teach Fab Lab basics quickly and simply with tangible outcomes

Teaching some digital fabrication topics might need considering of lots of constraints in the activity, which might be difficult to achieve in an open-ended project format. Moreover, when the project is open it is hard for the instructors to evaluate what equipment the groups will require, which slows down the process. Besides, due to children's unfamiliarity with the potential of the Fab Lab, they might either be unable to generate ideas, or generate non-feasible ideas. While familiarity with different forms of digital fabrication might or might not help the participants to come up with (feasible) project ideas, it is a stepping-stone toward making things in Fab Labs. Therefore, we recommend instructors introducing different activities at the beginning, including laser cutting, vinyl cutting, and 3D printing, so that children can create a variety of small items quickly, thereby reducing their dependency on instructors for future tasks. This may also enable instructors' skills and experiences to correspond with children's concerns and interests. Furthermore, based on our findings, children who follow this path are more likely to experience and acquire some skills.

Establish and emphasize children's long-term learning

The concepts central in digital fabrication can be too complex for children to understand, and children might engage in a lot of activities without fully comprehending what they are doing. Thus, it may be difficult for children to remember what they did and to repeat it. In line with the learning objectives, the instructor may choose to teach the use of software or machines in a variety of manners, such as telling children to press buttons every time or teaching them to press buttons while explaining the reason for doing so while allowing them to try it on their own, which might help children to remember what to do next time. After a few sessions, when we found out that the instructors operated the machines for the children, or even designed and made things for them, we intervened and clarified that this was not in line with our objectives. To avoid such situations, instructors should be aware of the values and goals for children's learning and know where and when to provide support.

Devise strategies (or ground-rules) to balance children's and adult's decision-making

During the projects, we had a number of issues with decision-making. The instructors had to guide the children gently toward feasible ideas without shooting down their suggestions, while making them feel engaged and enthusiastic about the projects. This required a delicate balance of negotiations, guidance, and steering towards the right way forward. In addition to this already complex configuration, the parents could veto decisions or become default-proxies for the children when they felt the decision-making process wasn't within their comfort zone or skill level. If parents step in to support their children, the children may easily lose any decision-making power and enthusiasm for projects. Researchers should inform instructors to what extent and how they seek to empower children's decision-making power and accordingly, instructors should use suitable methods, such as turn-taking, when making decisions to allow everyone to express their opinions.

Support instructors in incorporating reflection in the activities with children

Reflections on the activities, machines, experiences, and preferences of children were conducted on an ad hoc basis and with varying frequency by the different instructors in our data. If instructors are to be provided more detailed guidelines, and the activities are planned to be semi-structured, assigned times for reflections by participants and groups ought to be added to the activity structure and a set of questions to capture a wide array of reflection ought to be added to the instructor guidelines in order to deeper learning and understanding. In this way, participant reflections are linked with activities and initiated often enough, revealing also to instructors' issues and challenges as they arise and enabling instructors to anticipate upcoming challenges.

Create instructors' guidelines together with the instructors

Instructor's guidelines should be designed to support diverse instructors' work with children in various makerspace and Fab Lab settings and contexts. Consequently, when researchers/practitioners advocating for children's genuine participation arrange activities, a workshop should be held beforehand with the instructors to jointly discuss, modify, and enhance the principles based on researchers'/practitioners' and instructors' mutual wishes, interests, and goals. Instructors as the end users of the guidelines can then decide how to use those, leveraging their personal values around their roles and responsibilities while striving to create a supportive and friendly atmosphere for children. Fluidity in the instructors' roles can also be an effective technique when working with children (Perez et al., 2020). Figure 5 summarizes our recommendations for enabling children's genuine participation in digital design and fabrication.

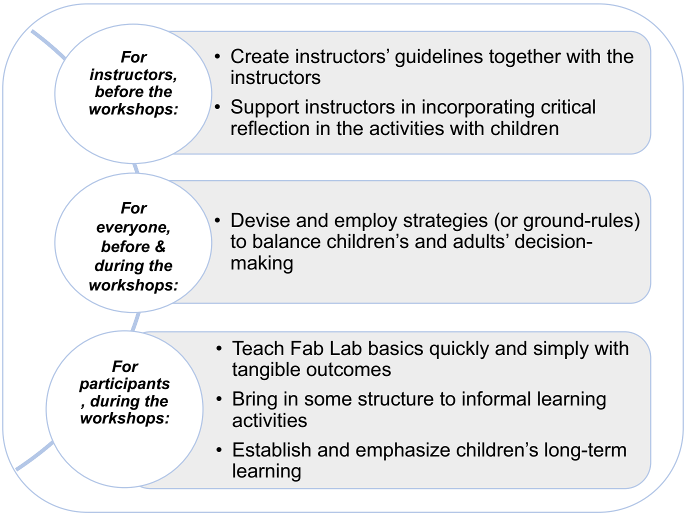

Fig. 5 The summary of our recommendations

Conclusion

This study examined technology and design education particularly from the perspectives of (1) education of digital design and fabrication; (2) children; (3) informal learning; (4) Fab Lab instructors' work practices, and (5) support for children's genuine participation. We approached such education "as an emergent rather than an established practice, with many open issues requiring research".[4] We concentrated on the context of Fab Labs and makerspaces that are increasingly available to children for learning and that usually engender a do-it-yourself mindset and people addressing their own issues and interests through digital fabrication and design. Instructors are needed to scaffold a variety of technical skills and expertise in these spaces. Their help is valuable for children but also for novice participants in general. In the current paper, we examine instructors' reflections on their instructing processes in informal open-ended Fab Lab activities that had been designed to enable children's genuine participation. As a result, we determined that support for instructors without a background in instructing children is crucial for enabling children's (genuine) participation. The instructors should not only be provided with guidelines, but also be included in the design of the guidelines for their own work to ensure that their personal values and expertise are incorporated. In addition, we stress the significance of involving instructors in designing the activities to balance their own expertise with that of the children.

The Fab Lab environment can be intimidating for novices; Fab Lab practices, and instructors manifesting those in their daily work, are in a central role to ease novice participants' entrance and learning curve. We argue these guidelines are valuable when working with novice participants in makerspaces more generally too, while future research is needed to specify which aspects might be entirely child specific. Additionally, we encourage researchers to explore the open-ended informal Fab Lab context for young children to better understand how to enhance instructors' roles, support instructors' work process, and

[4] As expressed in the aims and scope of this journal: https://www.springer.com/journal/10798/

develop innovative methods to support instructors in facilitating children's design idea generation. The informal open-ended projects are at the core of do-it-yourself digital design and fabrication, in which children should be encouraged to gain agency and become "digital innovators of the future" (Iivari et al., 2016), which can be considered to be among the goals of technology and design education more broadly.

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Declarations

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