Youth's Perspectives of Computational Design in Making-based Coding Activities

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ABSTRACT

There are increasing calls to introduce coding in K-12 in creative ways that provide opportunities for personal expression. Computational design projects include computational concepts fundamental to computer science to generate 2D and 3D models that can potentially be personally meaningful. We developed and implemented making-based coding activities for youth that combine computational design and 3D printing tools and allow the participants to design and fabricate free-choice projects. To investigate how young persons engaged in computational design and which aspects demotivated them, we used a mixed-methods approach that included semi-structured interviews and questionnaires. We took field notes and collected students' artifacts to triangulate the data wherever possible. The results show that 3D printing, creating unique aesthetics, enhanced personalization, and ownership of design models are crucial elements for engaging youth in computational design. We discuss the implications of our exploratory study and suggest directions for future work in developing computationally rich making-based activities.

CCS CONCEPTS

• **Social and professional topics → Computing education**.

KEYWORDS

computational design, 3D printing, constructionism, creative coding, computational making

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1 INTRODUCTION

Coding skills should be accessible to every individual for computational problem solving but also as a means for creative and artistic expression. Over the last years, there have been global efforts to foster computational thinking and coding skills in children and young people [11]. Besides efforts to introduce coding learning activities in K-12, there are increasing efforts to provide coding learning opportunities in non-formal and informal learning settings, in physical (Fab Labs, Makerspaces, Hackerspaces) and online spaces (Code.org, freeCodeCamp, etc.). Such initiatives aim at increasing access and participation in computing, especially for historically underrepresented populations.

Many educators in school and out-of-school settings often fail at engaging and empowering individuals in coding activities as they focus exclusively on technical aspects of computing. On the contrary, computational concepts and practices should be introduced in parallel with creative and real-life applications of coding rather than dull exercises. For this reason, computer science education research is often based on Seymour Papert's constructionism [27]. This learning theory emphasizes the importance of learning by doing and creating personally meaningful artifacts that can be shared and discussed with others.

According to Stager and Martinez [24], the learning philosophy behind the maker movement has its roots in Papert's constructionism. It emphasizes learning by creating personal projects through accessible yet powerful tools. A growing body of research related to creative and personally meaningful coding activities focuses on the making approach.

A relatively recent literature review on the promise of the maker movement in education [25] showed that coding learning activities are a popular area of maker education research. Types of making-based coding learning activities include but are not limited to the use of e-textiles [4], computational design and personal fabrication including laser-cutting [12] and 3D printing [5], and physical computing [17], among other tools and materials. Such learning activities can touch multiple subject areas in real-life contexts while fostering coding skills. For example, the work of Kafai et al. [15] demonstrates good examples of broadening the perceptions of youth towards coding through making with e-textiles. While designing electronic textiles, the students in the described study successfully used computational concepts and practices [3] and made connections of coding and computer science applications in their lives in general.

Other making-based coding activities include creating interactive objects through programming microcontrollers and microcomputers. In recent years, the combination of computational design and digital fabrication tools has been used by education researchers and practitioners to introduce computational concepts (iterations, conditional statements, etc.) to children and youth for generating 2D and 3D shapes that can also be fabricated.

By focusing on designing tangible artifacts, individuals can engage in making and start their own personally meaningful projects. Moreover, digital fabrication technologies can support the creation of objects with a quality comparable to that of industrial products [2, 23], empowering and motivating designers to bring their designs into the physical realm.

This paper investigates the combination of computational design and 3D printing for making functional and artistic projects in the service of coding education. We designed, implemented, and evaluated computational making workshops [14] with youth aiming to answer the following research question:

RQ: How can computational design and 3D printing be combined to provide personally meaningful coding learning activities for youth?

This study is a step towards better understanding the potential role of computational design in youth's education and lives. It provides directions for future work in developing creative coding learning activities and tools that are more aligned with students' interests and values. The following sections provide an overview of related work, the methods we used to evaluate the computational making workshops series, its description, and the participants' demographics. Lastly, we present the results of our study, discuss implications of the findings and their limitations, and suggest areas for future work.

2 BACKGROUND

Programming is undeniably an important element of computing, and the ability to code is becoming a basic literacy to understand an increasingly automated and digital world. In addition, coding is also a form of creative expression even though it is often seen exclusively as a skill for expertly trained individuals [30].

John Maeda argues about the expressive potential of computers [22] and the role of programming in modern designers' skillset [21]. Computational design, for example, requires the use of computational concepts (e.g., iterations and conditional statements) in order to generate visual representations of 2D and 3D models. These concepts can add "precision and automation, generativity and randomness, and parameterization" [12] to CAD (Computer-Aided Design) models generated through computational design tools which allow the creation of complex geometries that impress.

Integrating computational design into mathematics and art lessons seems to be a promising combination to engage students in these areas [33]. Sendova et al. [32] provide examples of computational design in the service of creative and artistic experiments, suggesting that in such an environment, it is easier to experiment with abstract concepts like colors, harmony, and tensions. The authors consider computational design tools a glass box and a means of learning through understanding models besides artistic creation [32].

Computational design in educational contexts dates back to the 1980s when Logo, the first educational programming language, was developed to introduce coding and mathematics to children through design [27]. Constructionist coding tools for digital design activities like Turtle Art (turtleart.org) allow creating artistic 2D images through mathematics, coding, and turtle geometry. Turtle graphics have been widely used for learning activities in the service of coding and mathematics education for decades [9, 28]. Today, modern computational tools that inherit Logo's educational philosophy and can combine "Turtle Geometry", "Dynamic Manipulation," and "3D Space" have been developed [19], paving the way for creative coding learning activities for 3D design.

Creating computational design models requires algorithmic thinking skills, pattern recognition through identifying graphic and coding patterns in generated 3D models, breaking down complex 3D models into sub-parts, and abstraction by implementing parametric procedures [19]. Spatial thinking skills are also necessary to manipulate a generated model in the three-dimensional space [20]. Previous studies have shown that using computational design tools can offer abundant opportunities for students to use computational practices like debugging, writing structured code, and using indentation [5]. A multiyear study investigated "creative computation" to equip pre-university students with the right computational tools for entry-level college. The study's findings show that the possibility to participate in projects that provide space for creativity in artistic contexts allowed students to efficiently use simple computational concepts to create highly expressive media [34].

Moreover, computation has expanded to reach product design and personal fabrication. Computational design tools enable the generation of models that would be impossible to achieve with traditional non-programmable CAD or design-by-hand methods. Combining coding and digital fabrication in a product design context might be an efficient way to introduce various applications of coding and highlight its creative potential. Such tools include educational technology innovations that allow moving coding learning activities from personal computers to programmable tools and the creation of tangible, often interactive objects. Eisenberg, a pioneer of introducing digital fabrication in education, argued that a maker-centered computing education would combine computing with creative technology innovations like 3D printers and other machines [8].

Computational design tools can enable youth to create more complex, innovative, and expressive projects according to their style and ideas. Some successful approaches for combining coding and digital fabrication to broaden perceptions about programming have included the use of computational design tools and laser cutters. Dittert et al. [7] used this combination to empower 13 to 14 years old girls in computational design and digital fabrication through the lens of making jewelry. Similarly, Jacobs and Buechley [12] designed and implemented a fashion workshop that combines computational design, digital fabrication, and crafts for young persons. The evaluations of their workshops with young people [13] and artists [12] show that youth perceptions in coding have changed and sparked their interest in future computational projects connected with their lives. The authors argue that the way we dress and what we wear are forms of personal expression, communicate who we are, and provide powerful contexts for learning.

Combining 3D printing technologies and computational design leads to longer manufacturing times but allows more space for creating complex, sophisticated, three-dimensional models. Furthermore, 3D printers are considerably cheaper than laser cutters and already found their place in formal and non-formal learning environments [10]. Modern computational design tools provide easy ways to bring digital design models into the physical realm by easily exporting the design files in formats suitable for digital fabrication. For example, BeetleBlocks [18] and BlocksCAD [1] are two popular online block-based computational design tools aimed primarily at children. They allow the end-users to export their 3D models in STL format and effortlessly transform them into specific instructions for the printer through free and open-source slicing software. Typical non-programmable novice-oriented CAD tools provide novice-friendly interfaces for 3D modeling (e.g., TinkerCAD), but they offer limited options for customization and automation of processes (e.g., for the creation of iterative partners).

Besides, the combination of 3D printing and computational design provides authentic project-based learning activities that touch different STEAM (science, technology, engineering, arts, and mathematics) content areas, and can foster computational thinking skills [6]. Three-dimensional technology has been used to motivate and empower children and youth in STEAM-related learning activities by promising a tangible product [16] that can be personally meaningful to students and has an industrial-like quality [2, 23].

However, most studies on students' perspectives of computational design in educational contexts focus on learning activities with predefined design topics, report only on digital artifacts, or use digital fabrication tools like laser cutters that come with limitations (they are more suitable for 2D design) and are less accessible to wider audiences due to higher costs. We aim to fill in this gap by conducting an empirical investigation that looks at young persons' perceptions of computational design and 3D printing for creating projects of their choice. We hope that findings from this study will inform the development of such activities for educators and researchers interested in combining these powerful tools.

3 METHODS

This study investigates how youth engages in computational design and 3D printing. In the following sections, we present the description of the computational making workshop we designed, implemented, and evaluated, including the materials and tools used during the workshop, the demographics of the participants, the data collection, and analysis procedures.

3.1 Description of the computational making workshop

The computational making workshop provides coding and 3D printing learning activities. It took place in out-of-school learning environments, namely, a fab lab and computer science lab with access to 3D printers and laptops. It was designed based on the constructionist approach [27] and making [26]. It aimed at engaging individuals in computational making [14] while providing "low floors", "high ceilings", and "wide walls" [30]. The workshop participants could design and fabricate a project of their choice based on their own ideas and imagination. The tutors who contributed to the workshop's implementation acted as facilitators of the learning activity instead of instructors. The workshop aimed to introduce computational concepts and practices to youth and broaden their perspectives about coding activities by designing and fabricating personally meaningful projects.

3.1.1 Structure of the workshop. The workshops took place during 4 school days in 4-5 hours sessions per day, including breaks and the possibility to stay longer at the labs. The workshop was structured as follows:

- Day 1: Introducing applications of computational design and 3D printing tools, materials and their properties, experimentation with block-based CAD commands, ideation for potential projects
- Day 2: Experimentation with computational concepts, discussion on computational practices (e.g., creating structured and readable code), applying computational concepts in the intended design
- Day 3: Experimentation with text-based computational design tools, transferring the previous project to the text-based environment OpenSCAD through a built-in application of BlocksCAD, the continuation of individuals' projects
- Day 4: Completion of individuals projects, demonstration of participants' projects, discussion, and reflection

3.1.2 Tools and materials. The fab lab and computer science lab provided access to laptops and computers, 3D printers, different kinds of printing filaments in color and properties, paper sheets, and writing utensils. The computational design tools that were used during the workshop were BlocksCAD and OpenSCAD. The first tool is a free online platform with an interface resembling Scratch. The second tool is a text-based open-source software used for computational design. Both BlocksCAD and OpenSCAD enable the creation of CAD models intended for fabrication for novices and more experienced designers, respectively. Their generated 2D and 3D models can be previewed but cannot be interactively modified by mouse. These computational design tools enable easy adjustments through changing the parameters in the code that generates a 2D or 3D model, e.g., by changing the parameters for length, width, and height that define the volume of the generated 3D model. Furthermore, they are popular choices for research and education purposes as they allow the creation of 3D models in STL format, which can be imported in accessible slicing applications for 3D printing (e.g., the open-source slicer Cura).

3.2 Demographics of workshop participants

In total 27 students (14 boys and 13 girls) 13-17 years old participated in the computational making workshop. The participants were from the Bremen/Oldenburg Metropolitan Region and got informed about the workshop via our email or during their internship at our partner fab lab.

18 of the 27 workshop participants stated in a questionnaire that they had experience with some form of coding. We discovered during the interviews that some students only used CSS and HTML,

which are not programming languages, so they never used computational concepts like iterations and conditional statements. 12 of the 27 workshop participants stated that they had some experience with 3D printing (mainly the ones who were doing their internship at the fab lab).

3.3 Data collection

Semi-structured, in-depth interviews were carried out with six boys and three girls on-site after the 4-day workshop series and lasted 25 to 45 minutes each. The interviews were structured around the following topics: Personal interests of the participants, previous experience of the participant in coding and design, overall experiences from the workshop, working with different types of computational design tools, and challenges during the workshop.

Furthermore, we collected questionnaires about the participants' learning experience and preferences, their design files and photos of their fabricated projects, and made field notes during the workshops. In some cases, due to time constraints and providing technical support to the workshop participants, a memory protocol was used to record our observations after the workshop. Our reasoning for including these parts in the report was that they offered valuable insights on computational design. We did not conduct interviews and field observations with all student participants, but we did draw on our own experiences during the workshops to interpret and represent their experiences.

We followed good practice guidelines for interviews with adolescents according to [29]. All participation was voluntary and involved informed consent.

3.4 Data Analysis

We applied both inductive and deductive approaches and methods for categorizing and coding. The initial set of deductive codes included: computational elements, attitudes toward computational design and type of tool, personally meaningful projects, and encountered difficulties. For the content analysis of the collected data, we used the software MaxQDA. We were able to break down the interpretation process of data into smaller parts, which can be evaluated by other researchers and checked for inter-coder reliability. From the beginning of the study's design, the first two authors were in close collaboration to design, conduct, and evaluate the different types of data. They engaged in an iterative process of making notes on the manuscripts and comparing codes during weekly meetings to ensure we reach to agreement. Wherever possible, we triangulated our data to facilitate a better understanding and capture a more reliable empirical picture of our findings.

4 RESULTS

The analysis of our data led to insights into how youth engages in personally meaningful computational design projects and which aspects are disengaging them. Regarding the engaging aspects we briefly focus on three key themes: Empowerment through digital fabrication, ownership of the designs and computational aesthetics. For disengaging aspects in computational design we briefly focus on the following key themes: High cognitive load/preferences for collaboration, existing designs, and time constraints.

4.1 Engagement in personally meaningful projects

The workshop participants often created more than one project to fabricate. 8 out of the 27 workshop participants designed objects that had a practical use. These projects were related to technology equipment like tablet and cellphone holders, phone cases, headsets, and cable holders. The designed categories of projects often overlapped with other categories. These included models of famous figures, architecture, symbols, and emblems of teams, clubs, bands, and practical items for daily life.

The analysis of the surveys showed that, in general, the favorite projects of the workshop participants were related to entertaining activities and practical objects for their daily life like missing or broken parts of products, followed by projects related to fashion.

Figure 1: Fun projects of workshop participants

Figure 2: Headphones holder intended for daily use by a workshop participant

The least attractive topics for design seemed to be related to science projects and the creation of tools. The surveys revealed that both boys and girls participants would prefer to use 3D printers for projects related to fun activities and to fabricate missing or broken parts of existing products. After such projects, the workshop participants seemed to appeal the most to projects associated with their hobbies, including fashion design, sports and music.

Three workshop participants were very motivated from the beginning to create projects for their hobbies. One student participant, passionate about boxing, did several projects related to his favorite sport.

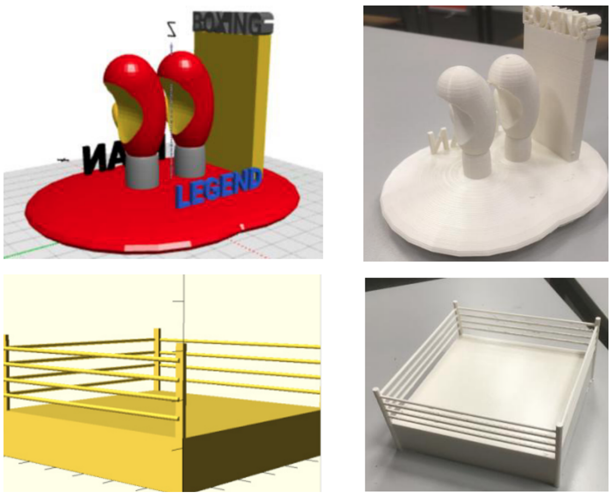

Figure 3: Projects inspired by the hobby of a workshop participant

Some workshop participants were motivated to create projects that simply looked "cool" and intended to use them in real life too. In the end, some had to compromise and adjust the size of the printed artifacts due to time constraints, costs, and the size of artifacts that our lab printers could support. A workshop participant stated:

> "... I designed the helmet for fun because it looks cool. Most likely, in the end, it's going to be my keychain, but yes, if we had a bigger printer, I would print it bigger and wear it. I would paint the helmet and wear it myself."

4.1.1 Empowerment. During the interviews, the workshop participants often mentioned projects to be "fun" and "cool". The intention of the workshop participants to fabricate their design ideas and use the artifacts in their daily lives indicate the importance of creating a tangible product as motivation in computational design. We believe that the 3D printing process itself was also a means of empowerment. Most student participants seemed very keen to use the 3D printers in our fabrication labs. The transformation of the digital design models into physical artifacts appeared to motivate the participants to challenge themselves and put great effort into creating sophisticated objects of high quality. The participants appeared to be very proud of their projects. Some took photos and video recorded the 3D printing process. They uploaded these pictures and videos on social media or sent them to friends and family. One participant also made a timelapse video of the printing process of their designs. The majority of the participants perceived their experiences during the workshops positively and seemed to be proud of their projects.

> "I would say for a beginner's project, that is pretty good. And you can always improve it when you put more time into it. But even for pros, I think that is good!"

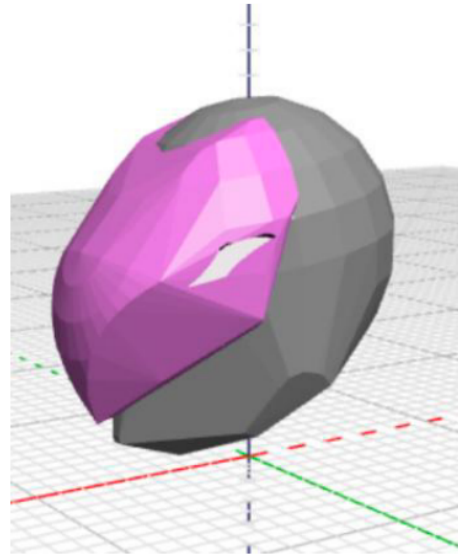

Figure 4: A 3D model of a helmet as imagined by a student participant

Two participants would share their projects in the hope of praise and because of their pride in their projects, respectively:

> "Maybe other people check them (the design models), and maybe they like them."

> "I am proud of my project. I am going to upload it..."

The willingness of the workshop participants to share their projects online indicates they might also seek recognition of their skills and developed ideas. It also indicates that they feel proud about their designs and their significance in the world as artistic or functional products.

4.1.2 Ownership of designs. During the workshops, the student participants concentrated on their projects and had concrete ideas on implementing computational concepts in their designs. Even when using works of others as a reference, they usually added their own elements and personalized their design. A workshop participant who created a horseshoe for her keychain based on an image she found on the internet, used iteration to enrich her project with decorative patterns. A participant stated:

> "Even when there is the same model online, I would prefer to design it by myself. It is special to me this way."

Another participant argued that others could exploit their projects' potential value and wished to maintain the possibility of using their model for profitability. Other participants did not want to upload their design models because they believed it was unfair for people to have access to use and modify them without participating in the design process.

> "It is almost a pity to upload it just like that. Someone else could just easily copy it and even change it."

4.1.3 *Computational aesthetics.* At the start of the workshop, all workshop participants experimented with computational design commands through short tutorials to get the basic knowledge to proceed in more sophisticated projects. Two workshop participants we interviewed did not have a concrete idea of a project they wanted to design, and they preferred to keep experimenting with the computational design tools and create more abstract and artistic design models. The workshop participants seemed to enjoy experimenting with computational design without a given topic.

> "... No, I had much fun trying and testing it out..."

> "I do not like to stick to step-by-step tutorials. I prefer to have more freedom and do my own stuff."

One participant of the workshop emphasized the unique aesthetic possibilities of a generated model through computational design. According to her, most CAD projects are "just things", but computation can create unique projects that do not yet exist.

> "Scrolling through Thingiverse [an online hardware repository], you could see most of the projects again and again. Not really new stuff or anything. Everything derives from reality. You could see things like cars and apples but nothing new, only things that you have already seen."

> "I think it's pretty cool that you can work long hours and end up with an end product. I am also interested in art and also draw a lot in my free time, and you can relate to this."

A participant seemed to have no interest in coding activities before the workshop, but designing with computational design tools seemed to appeal to him.

> "Previously, I thought programming to be a bit boring. I thought that just typing commands is not something special. Now that I learned how this works and all the complex and interesting things you can do with it, I am more interested in it."

While workshop participants were experimenting with computational design, we captured cases where aesthetically pleasing forms and shapes were achieved unintentionally by the workshop participants:

Interviewer:

> "That is an impressive design. How did you create it?"

Workshop participant:

> "I do not know. I just dragged some blocks, and this appeared."

4.2 Disengagement aspects

4.2.1 *High cognitive load/preferences for collaboration.* The workshop participants with no profound experience in coding found it more challenging to grasp computational concepts like iterations and conditional statements. Some students with weak mathematics background managed to successfully use computational commands but struggled with arranging their models in the 3D space. When challenges were too difficult to overcome, the tutors and and the rest of the student participants often provided support. One participant stated that he wanted to improve his 3D design and printing skills to create more advanced projects, but only as long as he "wouldn't get a shock" from everything he has to do to make one. Besides, he expressed his preference for working with others instead of by himself. According to him, writing many lines of code is too frustrating but coding as a social activity takes off some burden of this frustration.

> "If I would keep working with these and I wouldn't get a shock to make the things I need to do, then probably I would like to learn more about them (computational design and 3D printing). I'm just a person; I wouldn't be able to write a thousand pages of code. I wouldn't try it alone."

> "For example, scaling and rotating were very difficult for me because they were completely new, but with a little help, everything was okay."

4.2.2 *Existing designs.* Many workshop participants stated that some of the projects uploaded on Thingiverse are "too complicated for non-experts to design" and would rather download them instead of making them by themselves. The participants seemed to find designing products that required high precision more frustrating:

> "It depends on how complex a product is. When it is not too difficult, I would like to try to design it by myself. The problem is that sometimes you have to be very precise about the measurements. When you create some stuff, you do not have to worry about the length being 15cm or 4cm. When you want to create some spare parts, though, even a small difference like 2.9cm instead of 3cm can have a bad effect on your product. These kinds of designs I would rather download and print."

4.2.3 *Time constraints.* Another participant reported that he liked the activities, but his daily life would not allow him to engage in similar projects more than once per month. Two participants were not motivated to continue working with computational design and 3D printing and improve their current skills. The lack of motivation was based on the assumption that non-professional designers/programmers cannot achieve high-quality results. According to them, it is more convenient to buy a product in some cases instead of making it. Moreover, access to the existing design models was demotivating for making them.

> "...you start to design something, and then you have all these problems that occur, and sometimes you cannot proceed. Or, you cannot design a spare part, and then you end up buying it. Or even when you can design it, and the project is not expensive, like 100 euros, then you just buy it."

> "...if there is already a model on Thingiverse, why should I put so much work to make it?"

A third participant stated that she would put effort into designing something that she really wanted if this design model was not available.

> "When there is something important to me and would make me really happy to have it, and there was no model online, then I would design it and print it myself. At least I would try."

Another participant stated that he does not see himself using programming or computational design in his free time, but only if he would choose a profession that requires such practices. All but one participant welcomed the thought of including more computational design activities in school. Three participants also wished for more information about career opportunities for computing related professions.

5 DISCUSSION

This explorative study aimed to better understand which aspects of computational making engaged youth in computational design, a topic that is still underexplored in computing education research [31]. Previous qualitative evaluations focused on computational 2D design and fabrication of jewelry [7] and fashion [12] artifacts. We aimed to build on previous work with examining computational design with 3D printing technology and no predefined topic for projects, which might provide new possibilities for creative endeavors in the three-dimensional space. Encouraging the workshop participants to create individual projects entirely based on their ideas and interests was challenging for the facilitators of the workshop but highly rewarding in terms of engagement and motivation.

The findings from our research indicate that computational making activities are promising in engaging students in learning activities that connect to their lives and interests. The workshop participants had the possibility to design and fabricate at least one project of their choice, which led to a wide variety of project types. The workshop participants created fun and artistic projects for decoration and fashion and practical projects intended to be used in the daily life of the participants, like phone cases and tablet holders.

Based on the questionnaire results, it seems that both girls and boys prefer to create projects for fun and entertainment as well as more practical ones, e.g., for the replacement of broken parts of a product or similar. Therefore, it might be a good strategy to consider such projects in computational making learning activities to engage and maintain underrepresented populations in STEM when there are limited possibilities for creating projects of their choice, e.g., in youth's formal education.

As shown in previous studies in making-based learning activities, 3D printed artifacts are of industrial-like quality and tend to empower learners in making things [2, 23]. The fabrication of computational design models of complex shapes requires the use of support material, which might negatively impact the final aesthetics of the 3D printed artifacts if they are not properly removed. Even though we anticipated that some participants might get discouraged by such a process, that was not the case. The design and fabrication of impressive geometries led to the empowerment of the participants who were proud of their artifacts and very often took photos and videos of them and shared them via messenger apps.

Personal computational aesthetics were particularly intriguing to workshop participants to create decorative patterns and iterative elements in the design models. This result ties well with a previous study on the combination of 3D printing technology and turtle graphics [31].

In addition, our findings from interviews indicate that students who find computational aesthetics particularly appealing tend to find standard and conventional projects boring. Unique computational ideas for models that cannot be found online seemed to appeal to them and make them stand out. The student participants also expressed their preference for computational experimentation instead of step-by-step tutorials with predetermined topics or designing models that required high precision calculations.

Even though computational experimentation seemed to be a compelling way to create and understand computational concepts and models, it raised questions about deep and sustainable learning. Computational experimentation should be used with cautiousness and allow space to verify their reasoning when using computational concepts, methods, and tools. It is critical to use educational tools to expand the learning possibilities inside and outside the classroom and avoid oversimplified projects that easily impress (e.g., see the keychain syndrome) [2].

The student participants communicated issues that would prevent them from engaging in computational design activities. These included time constraints and steep learning curves to master tools, lack of support by experts and their peers, and lack of motivation to create complex design models when these can be easily found online. Therefore, it is critical to provide tools, conditions, and challenges of suitable difficulties, considering youth's diverse experiences and preferences.

Overall, the evaluation of the questionnaires showed that the workshop participants enjoyed the workshop, and a third of the participants asked for more information about professions that combine computing aspects, which might be an indication that the computational making approach can broaden their perceptions about computing. However, more research is needed to effectively evaluate the impact of the developed concept on students' perception of computing.

6 LIMITATIONS

This study was an early exploration into how youth perceives computational design and 3D printing through the lens of computational making. This study was limited to a four days workshop experience of youth participating in the study. Due to time constraints and privacy matters with the workshop participants, we could only conduct post-workshop interviews with nine participants. All nine participants that we interviewed were student interns at a fab lab, and they might have been more interested in technology and computing than other young people.

The small number of participants only allowed us to use descriptive statistics. Therefore, we did not intend to support the replication of the results beyond the participants of our study but to provide robust evidence of the generalization of our qualitative findings when possible. This limits the power of our findings even though we have an indication about youth's attitudes towards computational making.

Another limitation of this work which is common in computing education research is the small and inconsistent sample of students in terms of their age and prior knowledge. A comparative study could focus on the different perceptions of computational design between experienced and novice young people of specific age groups.

7 CONCLUSION AND FUTURE WORK

Through a series of computational making workshops, we explored how youth engaged in computational design activities to design projects of their choice as a means of personal and creative expression. Personalizing projects and complex design possibilities in aesthetics seemed to be critical elements in engaging youth in computational design projects. These come with specific concerns regarding computational design in educational contexts, as aesthetically pleasing models can be generated and fabricated unintentionally. Moreover, different learning styles and preferences in design activities call for appropriate pedagogies, tools, conditions, and challenges of suitable difficulties, considering youth's diverse needs. The workshop participants enjoyed the concept of computational making workshops, and we believe this approach can contribute to efforts in broadening youth's perception of coding and its creative potential.

Future research might focus on larger-scale studies and evaluate young people's previous attitudes towards computational design before the designed intervention. Furthermore, computation has applications in nearly every aspect of our life. Thus, there are opportunities for developing computational making activities for poetry, music, and dance, besides design. In such learning activities, concepts like rhythm, creative writing, and computer-animated storytelling, youth could computationally model with popular, powerful, yet accessible tools (e.g., Scratch). We would like to see more initiatives that focus on computational making for creating social artifacts and activities in humanities as a form of expression that sparks imagination, creativity, emotions, and meaningful discussions.

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