

Learning through interactive artifacts: Personal fabrication using electrochromic displays to remember Atari women programmers[☆]

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ABSTRACT

In recent years makerspaces have gained traction as an environment where makers and tinkerers can freely create artefacts with digital fabrication tools. They are particularly suited for introducing new fabrication techniques because these spaces support hands-on experiences. Electrochromic displays are one such technology that has become possible to fabricate using new techniques and off-the-shelf tools which lends itself to be used in a workshop setting. Leveraging this development, we facilitated a makerspace workshop that introduced participants to this new technology. To limit the scope of the workshop outcome we used the little known history of female developers of video games (Atari) from the 1970s and 1980s as a design framing. The participants (undergraduates, 16 female, 2 male, aged 19–21 years) explored the Atari women's role in development and through this exploration they created artifacts using novel electrochromic displays as designed responses. Throughout the workshop participants answered daily questionnaires and kept records of their progress. Our analysis of the questionnaires and the resulting projects suggests that having a relatable and meaningful context increases both motivation and engagement of the participants. We discuss the extrinsic motivations that enhance engagement, and provide suggestions for introducing new technologies in the makerspace context.

1. Introduction

Making, learning, and makerspaces have been receiving attention in the HCI community over the last couple of years [1,2], and have explored across different settings, domains, and in different parts of the world e.g. Asia [3,4], America [5] and Europe [6]. Part of the reason why making has been celebrated is that making as a strategy allows for more inclusive access to technology, by lowering barriers to participation [7,8]. However, research has demonstrated that makerspaces and the making culture can also exclude users from participation. In such spaces and in the maker communities in general, there is a lack of gender, ethnicity, and age diversity [9,10]. Furthermore, the infrastructures available matter, for who has access to participate and engage with new technology [11]. And while there is initial research on makerspaces and inclusivity, recent research has reported a need for investigation into how new technologies fit into makerspaces, how they can be used for learning, and how teachers integrate Making into education [12–14]. While for most established fabrication techniques, such

as laser cutting or 3D Printing, a large amount of tailored instructions are available, novel materials and fabrication processes are relatively less supported. One of these is Electrochromic display technology, a new kind of electronic display that has the potential to become part of makerspaces and learning environments, as it is relatively easy and inexpensive to make.

Electrochromic materials are a specially engineered class materials that change their visual characteristics in response to electric current. They have been around since the 1970's but it has only recently become possible to prototype and fabricate with them using off-the-shelf tools [15]. This type of material can be used to fabricate an *electrochromic display* (hereafter referred to as ECD), which enables the creation and display of interactive printed graphics. These displays do not employ transmitted light, such as with liquid crystal, LED, or OLED displays, but rather, rely upon reflected light incident upon their surface, akin to e-ink displays. By applying a low, DC electric current, it is easy to switch between two graphic elements in the display, one of which is visible, while another is nearly invisible. Switching the polarity of the current

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changes which graphic is visible. It is possible to create an ECD with an ordinary, consumer-grade inkjet printer. But unlike graphic designs created on a computer and printed on ordinary paper, there are many steps of physical construction in designing and fabricating an ECD. These steps can be performed by non-experts (see Fig. 1), but to do so requires not only learning how ECDs are constructed but also about their capabilities and limitations (e.g., speed of transition, vibrancy of graphics, balance of display). ECD composition and constraints require designers to think differently about their designs to ensure the display works optimally for any given application.

Because ECDs are transparent, flexible and require only a small amount of current to change state (<10 milliamps), they lend themselves well to designers for design prototyping, Internet of Things applications, and e-textiles [16–18,55]. They can be printed in arbitrary, irregular shapes and sizes making them integrateable into artifacts that require non-rectangular or flexible displays. Additionally, because advanced hardware is not required to drive them (in contrast to e.g., LCD and OLED displays), they are easily driven using simple electronic circuits or prototyping platforms such as Arduino [19,20,56].

In this paper, we present the results of a workshop that aimed to introduce participants who are new to makerspace facilities and novel fabrication techniques, while also exposing them to the little-known history of female game developers at Atari and their role in history [53], which served as a design framing. We introduced electrochromic materials as another resource in a makerspace, to explore not only the design and execution of a making workshop for learning, but also how new types of technology can be added to the makerspace. We chose the history of the Atari woman as a design framing because we wanted the participants to have a story to tell, to attract people that are usually not coming to makerspaces (in particular, women students) and motivate them to return. The artifacts that the participants developed were exhibited publicly at a museum after workshop.

Specifically, we are interested in these questions:

1. How do the limitations of the ECD technology influence the design activities in the makerspace?
2. How does the prospect of a public exhibition impact participants learning outcome?
3. How does using Atari Women as the design framing impact the participants' learning context?

Our findings suggest that the learning environment of the workshop should allow participants to explore the new technology in a thematic context that is meaningful to them. Moreover, their experience is more salient if the artifacts they produce live on beyond the workshop. Furthermore, we found that when introducing these novel fabrication techniques to novices, the availability of instructional materials and especially experts is highly important. Not only can they help by demonstrating the correct fabrication procedures but also support the participants to recover from mistakes through explanation and guidance.

The paper is structured as follows, first we present related work in constructionism and personal fabrication. We then present how the workshop was conducted and what the participants were instructed to do along with a description of our participants, data collection and analysis. Following this we present the results in two subsections, the first presents the resulting artifacts and their chosen story, the interactivity and the fabrication, and the second subsection presents the results from the data analysis. Finally, we present a discussion of our work and present three points facilitators should consider when introducing new technologies in makerspaces.

2. Related Work

We turn now to related work on Constructionism and personal fabrication that informed our approach.

2.1. Learning by Making

Build on Piaget's constructivist theory that a learner is constructing knowledge from prior experiences and through interacting with the environment, Papert proposed his theory of Constructionism. In this theory, knowledge is constructed during the process of making artifacts that can be shown, examined, discussed, admired and probed. As a math teacher Papert wanted to engage his students in the same way art students were engaged in making and learning to make art. He used the programming language LOGO to let his students guide the actions and movements of a small robot "turtle" and saw it as a computational "object-to-think-with". For Papert the "turtle" functioned as a model for other objects, yet to be invented. From this work, constructionist researchers found that LOGO enabled learners to understand abstract

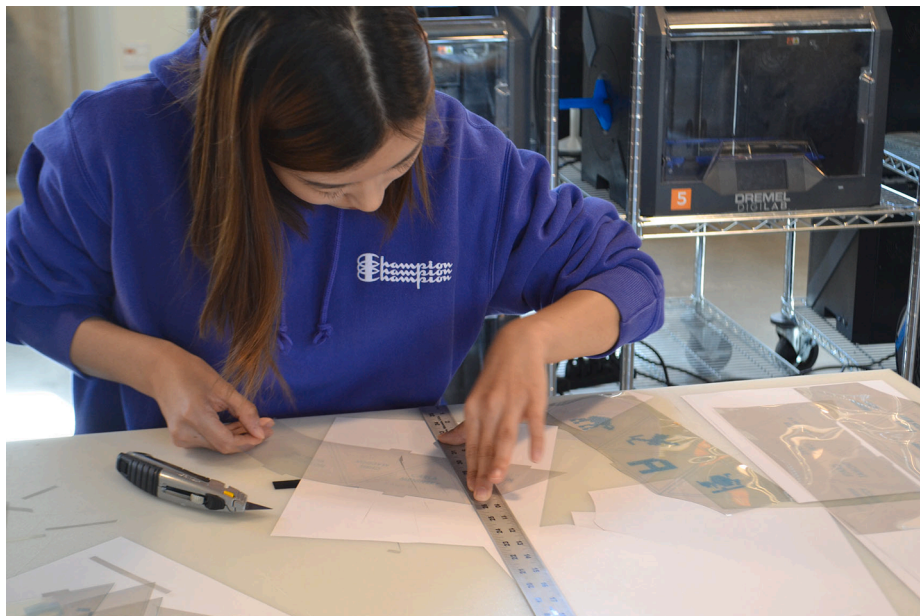


Fig. 1. Participant fabricating electrochromic displays.

mathematical concepts in more accessible, concrete and relevant ways. Instead of receiving knowledge, the learners were making knowledge, with an emphasis on *making*, which is in contrast to instructionism, in which learners receive knowledge through didactic instruction [21,22].

In 2016, Papavlasopoulou, et. al., presented a review of recent research on the Maker Movement and its role in formal and informal education [12]. Through search terms such as maker, making, makerspaces, movement, education, science education and a combination of the terms their meta-analysis found 2930 papers published between 2011 and 2015. They decreased this number to 43 usable studies by excluding irrelevant papers such as posters, non-peer reviewed and work-in-progress papers, and by using criteria proposed by Greenhalgh and Taylor [23]. Their review showed that the most common subject area for implementing Constructionism or “learning-by-making” is programming (32 of the papers reviewed had programming or programming in combination with another subject as the focus). Although most of the studies focused on programming, they still used tools such as basic electronics, Arduinos micro-controllers, and the visual programming language Scratch. They identified a need for further investigation into other tools for making, such as using digital and tangible materials [24,13,14]. Other tools used in the studies were 3D printing [25,26], laser cutting and circuit board design [27], sewing and conductive materials [28,29,13], and MakeyMakey [30,31]. Further, they found that few of the studies focused on gender issues or how making can benefit women.

2.2. Personal Fabrication

Personal fabrication is a growing area of research in HCI and was, in 2007, described by Neil Gerschenfeld [32] as “the ability to design and produce your own products, in your own home, with a machine that combines consumer electronics with industrial tools.” The rise is evident in the amount of research in or using 3D printers [33–37], lasercutters [38–42], CNC machines [43–45] to mention a few. Later, Baudisch and Mueller [46], describe four elements that are required for a fabrication to transition from industry to the consumer: (1) *Hardware and material*, (2) *domain knowledge*, (3) *visual feedback* and (4) *machine-specific*

knowledge. For a technology to become usable for personal fabrication the *hardware and materials* have to transition from the specialized equipment used in industry to one that can be used by a consumer. The expertise (*domain knowledge*) that industry professionals have should likewise transition into a form that is accessible to people with no expertise, for example, in the form of software. The software or system used should provide the *what-you-see-is-what-you-get (visual feedback)* principle. Additionally, the software should reduce the need for a physical skill, similar to how Digital Video editing software removed the need to manually cut and align films when editing films.

3. Method

We conducted a one week-long workshop (see Fig. 2) as part of a credit-bearing university course called a Directed Research Group (DRG) which took as its theme the women who developed Atari games in the late 1970s and early 80s. The results of this workshop where exhibited at a well-known local museum of Computing. We told the participants that the workshop was a part of a research project, and a learning opportunity for them to work in the maker area. In addition, we also told them that our roles would be both as teachers and researchers during the workshop. As the exhibition was not mentioned in the description of the course, we told the participants on the first day of the workshop. The university makerspace had a variety of very common equipment available (i.e., lasercutters, 3D printers, CNC machines, embroidery machines, vinyl cutters, etc.) that are well documented and for which a large variety of learning materials can be found online. However, we also added novel and not-so-well documented ECD fabrication to the curricula as a mandatory element. This was done to investigate the students’ engagement and learning with ECDs in a circumstance in which much of their exploration was done with minimal learning materials.

The main task for the participants was to create an artifact that celebrated the important contributions of women who developed Atari games in the 1970’s. To design and construct the artifact, the participants used different fabrication tools in the makerspace. Students had to form small teams of three, and each group was supposed to focus on one

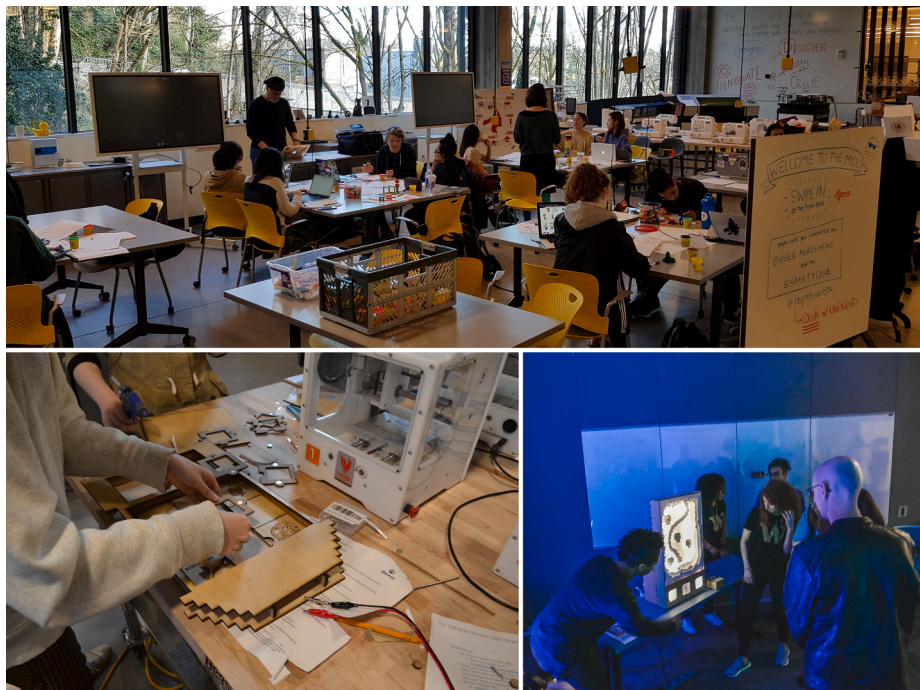


Fig. 2. Top: Participants brainstorming ideas using Lego and Play-doh. Left: The MixIt-Up project group is making sure electrical connectivity is working. Right: The Centipede project is being presented by group at the museum exhibition.

Atari game and the woman who developed it. This instruction was given to drive the design of their artifacts. As a result, the teams designed objects which captured and related to the story of the game and its creator. Participants first used low-fidelity prototyping methods such as sketching, clay modeling, or LEGO for idea generation and brainstorming. The ideas were then prototyped in cardboard before being digitally designed and fabricated in higher fidelity. As a means of conveying the stories, it was mandatory for them to also include ECDs into the designs. These had to be fabricated by the groups as well.

ECDs have some unique advantages and disadvantages. On the one hand, the displays are bendable, can be designed into all kinds of shapes (e.g., circles, triangles, irregular, etc.) and thus provide different affordances compared to regular display screens. For this course, we opted for the most basic construction method of an ECD, the vertical stack [15]. This means that the displays can only contain two different graphics, showing one at a time. Once a display has been fabricated, its graphics designs cannot be changed, which posed additional design challenges for participants.

All these elements - and especially the choice of ECDs - were selected because they follow the “low floor - high ceiling” approach, meaning that getting successful and engaging results is relatively easy but the technologies have a large potential for exploration and extension. Furthermore, the chosen topic has creative, playful, and engaging elements - “wide walls” - that allows for easy personalization and expression for every group. These approaches are in line with Papert’s vision of Constructionism.

Additionally, to highlight the histories of the Atari women engineers to a broader audience, the artifacts that students had created were presented in an exhibition at a well-known computer museum, two months after the workshop. While this workshop was part of a university course which would give the participants credits, we were interested in how the exhibition would impact the designs and learning outcomes.

3.1. Workshop Structure

We ran the workshop sessions from 9AM - 5PM, Monday to Friday, starting each day with a short introduction explaining the goal of the day. Brief expository lectures introduced participants to the workshop while still giving them enough time to generate ideas and fabricate. On the first day (Monday), we instructed participants on the design context of the workshop (Atari women programmers), introduced the makerspace tools and equipment available (e.g. laser cutters, 3D printers) and how to design and fabricate ECDs. Instructions were kept short to afford more time for participants to learn-by-making [21]. The participants also formed groups, discussed which woman or story to work with, and each participant fabricated their own ECD. This helped them to better understand the affordances and constraints of the display technology during design ideation. On day two, we instructed the students on sketching and modeling after which each group brainstormed, sketched, and modelled three ideas. These were presented to the rest of the participants and teachers for feedback. By midday, each group had selected one idea and started prototyping their artifact using the tools available in the makerspace. On days three and four, the participants had free rein to work on their artifacts. Close support was provided on an individual- or group-basis. This allowed each student or group to follow their own tempo and receive information when needed. On day five, We encouraged groups to take videos and photos, and to write down findings from their own research during the workshop. We asked participants to create a short 2- to 4-min video of their project, which was shown during a theater session in the afternoon. Students continued to refine their projects after the workshop, in preparation for the museum exhibition.

3.2. Post meeting and Exhibition

We held a followup meeting a month after the workshop, to ensure each group was ready and had all the required material for exhibiting

their artifact. During the meeting each group presented their progress and a list of things they needed help with to ensure they were ready for the exhibition. Additionally, the meeting was used to inform how the exhibition would progress, who would likely attend, and what each group needed to prepare for the exhibition.

3.3. Participants

18 (2 male, 16 female, age 19–21) undergraduate engineering students were recruited for the workshop. For this, a description of the workshop including short descriptions of the ECD technology and the Atari women framing was advertised on the university website. Interested students could sign up by writing a short motivational letter that included their backgrounds, their technological experience, their knowledge of gaming and Atari, and their expectations of the workshop. The 18 participants were selected by the workshop facilitators based on these letters. All participants had taken introductory courses in programming and eight students had taken courses in human-centered design, interactive systems design and technology, or both. No participant had prior experience with makerspaces and their tools, nor with ECDs.

3.4. Data Collection

The participants answered a pre-workshop questionnaire, and completed daily reflections during the workshop in the form of questionnaires with open ended questions such as “What was difficult/ easy when you were identifying a focus for your design?”, “Describe an important “a-ha” moment from today. An “a-ha” moment is a situation where you learned something, solved a problem, found a way to go etc (please write 5–10 sentences)” and “What was the most challenging aspect with building your artefact today? Challenges with technology, machines, materials etc”. Each group was asked to keep records in form of a notebook throughout the week capturing their progress, information gathering, and the story of their artifacts. Participants documented their work with photos and video throughout the workshop and the exhibition. We obtained permission from participants to use their images and photos for dissemination.

3.5. Data analysis

We used a two-step, grounded theory approach to analyze and code the questionnaires [47]. In our initial coding we identified sentences or words that relate to learning about new technologies and tools, curiosity and engagement, and collaborative explorations. We identified 22 categories (see Table 1) that were sorted, compared and filtered to three salient themes (*structured learning*, *relatable context*, and *extrinsic motivation*) which will be described further in the fabrication environment

Table 1
Initial categories identified in questionnaires, listed by the themes they were sorted into.

Structured Learning	Relatable Context	Extrinsic Motivation
Fixed expectations	Meaningful context	Being able to show off work
Ideation and Prototyping	Overcoming difficulties	Make a complete project
Novel technology	Approachable people	Having a goal
Learning new things	Collaborative	Different skillsets
Experience is rewarding	Meeting likeminded people	Interesting technology
Workshop was fun/cool	Free expression - Freedom	Experiencing firsts
Working in small groups		
Hands-on		
experiencing		
Teaching others		

section. We analyzed each participant's self-record of their progress and photographs taken during the workshop to understand how the use of ECDs affected the project designs.

4. Results

4.1. Artifacts

To answer the first research question, we present the final artifacts that the students exhibited at the museum, and analyze them with respect to how the *story* that the students wanted to tell informed their design and use of ECDs, how *interactivity* was implemented and used with the displays, and finally how ECDs factored into the *fabrication* of the artifacts.

4.1.1. Story

Each team built a project using a game or the story of Atari women programmers in gaming as its design framing. Some project artifacts combined both. A key part of the design work was for participants to identify what to incorporate into their design as well as whether their project focused on the subject of the game or of the Atari women programmers. As noted above, a selection of these narratives were presented to participants during the workshop introduction. Interestingly, no group focused on the same context or game. A brief summary of their projects provides a glimpse into the kinds of artifacts the teams created.

The *SukiLee* artifact comprised an approximately 50 cm by 60 cm picture frame designed in the shape of the workshop's "Atari Women" logo (see Fig. 3, right). In the large frame two smaller frames, a square and an irregular shape, are attached. The two smaller frames contain ECDs. Suki Lee was the first Chinese-American programmer to work for Atari, yet her stories are hardly known by anyone. The participants wanted to emphasize Suki Lee's contribution of *Donald Duck's Speedboat* game for the Atari 2600 gaming platform. This game was only released in Brazil and never internationally. Further, the game was only published in a small batch and thus is very rare. Because the game was only released in Brazil it was largely "invisible" to the wider public. The participants developed an ECD with the silhouette of Suki Lee's face and one with the cover graphics of the *Donald Duck's Speedboat* game. The displays can shift from portraying a visible image to hiding the image, depending on a shift in electric polarity, triggered by a distance sensor. The participants developed the artifact so that the graphics are invisible until viewers approach the frame within 30 inches. This artifact focuses on Suki Lee and her circumstances surrounding the development of the *Donald Duck's Speedboat*. The participants leveraged the ECD's ability to make graphics appear and disappear as a feature of the design, thereby manifesting Suki Lee's story.

The *BugBox* artifact is designed as an interactive moth. Spreading its wings opens the box (see Fig. 3, left). Inside the box are several triangular-shaped ECDs. Their design is a nod to the computer scientist Grace Hopper, who found the first bug (a moth) in a computer system. The participants designed and fabricated 13 ECD pieces, each bearing the name of a female Atari programmer. Each of the display pieces can be activated by placing them on electrical contacts situated upon the moth's wings. The shape of each display piece echoed the shape of a moth, leveraging the capability of ECDs to be created in irregular shapes, thus creating a coherent design.

The *Spider-Man* artifact comprises a physical representation of the original digital user interface of the *Spider-Man* game and thus is designed as a building facade, on which Spider-Man is jumping around. On the facade there is one door and 12 windows; each window containing either a hand-drawn graphic or an ECD (see Fig. 4, left). The participants modelled and 3D-printed two characters (Spider-Man and Spider-Gwen), inspired by the *Spider-Man: Into the Spider-Verse* movie. Magnets embedded in the building facade allow the two characters to "jump" around the house, activating the ECDs. Each display is designed with a logo from a game developed by Atari women and text that shifts between the name of the game and the name of the developer. This artifact incorporates the stories of four different women who developed games, namely Laura Nicolich (*Spider-Man*), Patricia Goodson (music in *Pac-Man Jr.*), Betty Ryan Tylko (*Pole Position*) and Noelle Alito (*Moon Patrol*) while drawing inspiration from the *Spider-Man* game in its physical appearance and interaction. By designing and fabricating an ECD for each of the Atari programmers, participants engaged with multiple historical narratives, incorporating them into their Spider-Man centric design. Similar to the *BugBox*, the participants leveraged the ability to fabricate ECDs in any shape or form, thereby enabling them to integrate the display neatly into the windows of the building.

The *MixIt-Up* artifact is a laser cut puzzle game allowing a player to create various characters, all based on the original characters in Dawn Epstein's *Strawberry Shortcake* game (see Fig. 5, right). Following the "easter egg" concept from gaming culture, which became a way for developers to embed "secret" surprises into games (often displaying their own names), *MixIt-Up* also has an easter egg, thus incorporating a multi-layered story into the artifact. The *Strawberry Shortcake* video game was created at the same time as *Care Bears*, both by Parker Brothers, who employed two women game developers, Laura Nikolich and Dawn Epstein. These two games both targeted girls, however Parker Brothers decided not to release *Care Bears*, since they believed that too few girls played games to make it financially viable. To create the ability for players to mix-and-match characters, this team laser cut multiple pieces of wood which, when sandwiched together, would create physical depth and increased sturdiness in the game pieces. Six pieces of the

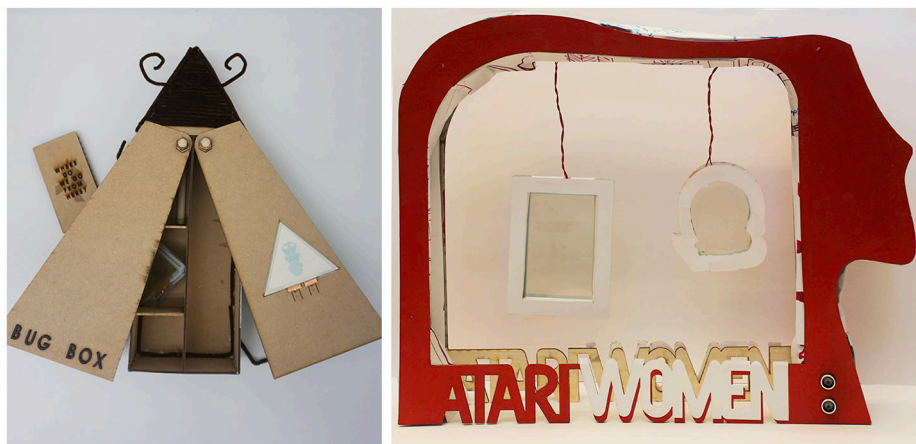


Fig. 3. Left: BugBox artifact with wings slightly open and one display placed on the wing. Right: Suki Lee artifact with both ECDs powered so the graphics are not visible.



Fig. 4. Left: The *Spider-Man* artifact features a building facade with multiple ECDs and two movable, 3D-printed characters. Right: The *Centipede* artifact is the physical representation of the 2D game with mushroom-shaped electrochromic displays taking the form of shootable objects. A laser-cut controller selects which character is activated.

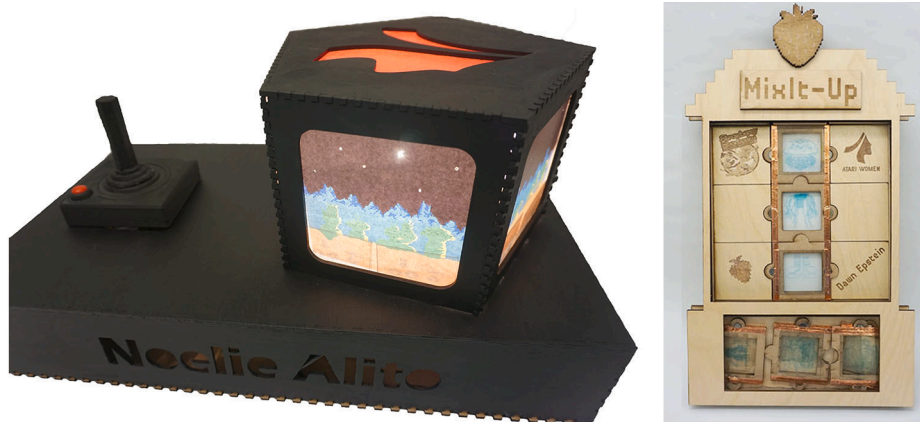


Fig. 5. Left: The *AlitoLamp* artifact with illuminated lamp and a 3D-printed joystick. Right: The *MixIt-Up* artifact used multiple ECD pieces to create a “remixing” exploration of characters.

puzzle were fabricated containing four different characters. One of the characters was the “easter egg”. As with the *Spider-Man* artifact, this game linked both the developer’s historical narrative and gameplay. The interactivity echos the gameplay of the *Strawberry Shortcake* video game in physical form. At the same time, the ECDs were designed to be replicas of the characters in the game. As with both the *BugBox* and *Spider-Man* projects the project teams utilized the ability to fabricate easily-powered ECDs in custom shapes, taking advantage of the fact that the displays are very thin and are easily integrated with other materials (in this case, laser cut wood).

The *AlitoLamp* project is an interactive lamp which incorporates a 3D-printed joystick (see Fig. 5, left). The participants honored the work of Noellie Alito who, together with Mark Acherman, developed the *Moon Patrol* game released in 1982. *Moon Patrol* is a side-scrolling game in which the player controls a moon buggy while avoiding obstacles on the moon’s surface. The project comprises a five-sided lamp and a 3D-printed joystick mounted on a box. Windows on the five sides support

lunar landscapes as normal printed graphics and transparent ECDs through which the landscapes are visible. This creates the illusion that the rover is appearing and disappearing on the lunar landscape as it traverses around the lamp, imitating the side-scrolling format of *Moon Patrol*. In contrast to the other artifacts, the *AlitoLamp* only focused on the game. Similar to the *SukiLee* artifact, the *AlitoLamp* uses the affordance of appearing and disappearing, creating the illusion of interactive printed graphics. Where the *SukiLee* artifact related the invisibility of women the *AlitoLamp* artifact combined the displays with ordinary printed graphics to create “interactive” printed graphics.

The *Centipede* project is an interactive light box that contains both digital technology and paper crafting materials. The artifact was developed as a physical representation of the game *Centipede*, created by Donna Bailey. Donna Bailey worked at Atari’s coin-op department where she experienced an unwelcoming, male-dominated work environment. The team incorporated cut paper elements to create an illusion of depth and parallax, as is seen in platform games (see Fig. 4, right).

They fabricated seven ECDs, four of them being mushrooms from the game and three of them being the player's character at different locations. The mushroom displays contained phrases or words (i.e., "Boys Club", "Lazer", "Wage Gap" and "Narrow Minded") symbolizing the bad experiences Donna Bailey experienced during her time at Atari. The three bottom displays were created to symbolize a character that can have three positions. These displays were placed adjacent to each other in a wooden frame located at the bottom of the artifact, whereas the mushrooms were scattered in the central window area around the centipede cutout. A smaller box with three buttons attached to the main enclosure functions as a game controller, incorporating buttons that move the character left and right and allow it to shoot at the mushrooms. Similar to *AlitoLamp*, *Centipede* focuses solely on the video game as an inspiration for its physical appearance and interactivity, but adds context in the form of the phrases associated with each of the mushrooms. Similar to the *SukiLee* artifact, the *Centipede* artifact leverages the ability to create ECDs in irregular shapes; the mushroom displays were fabricated and cut out in the shape of a mushroom.

4.1.2. Interactivity

The interactivity of each of the artifacts was linked to the electrochromic displays. ECD display technology's switching capability lends itself to being used for interactivity and each artifact did incorporate this feature.

The *BugBox* artifact required the user to manually place the ECDs onto the artifact to activate them. This created a tangible interaction, through pressure applied by the fingers to ensure a conductive connection between the artifact and the displays. One wing of the artifact had a battery holder attached to its underside, with two wires going through the wing to two pieces of conductive tape. The conductive tape affixed on the wing allows a player to randomly select and orient the displays and see the different graphics printed in the displays. This is a simple, yet effective use of the fact that ECDs need very low power to actuate, in contrast to the advanced electronics other display technologies require. Thus, simple physical interactions can be easily designed.

In contrast to *BugBox*, which derives its interaction from physically placing ECD displays onto metal contacts, the *AlitoLamp* incorporates a push-button. The button initiates an activation sequence that imitates the moving moon buggy. The push-button and each of six displays in the lamp assembly of the artifact were connected to an Arduino microcontroller, which allowed the team to program how the displays were switched, upon receiving an input from the button. The Arduino software sequentially shows only one display at a time, thereby creating a simple animation that gives the illusion of a moon buggy driving around the lamp. This artifact utilizes the ease of driving multiple ECDs with off-the-shelf prototyping platforms.

The *SukiLee* artifact incorporated a distance sensor to switch visibility of the displays, which was the locus of interactivity in the artifact. By connecting the two displays and a distance sensor to a microcontroller, the group was able to use proximity for interaction. The silhouette of Suki Lee and the graphics from the *Donald Duck's Speedboat* appear when viewers move close enough to it.

The *MixIt-Up* artifact uses a similar technique to activate the displays as *BugBox*, but still managed to do so in a more complex manner. The group laser cut smaller frames for their character pieces, and their design included mounting points for small magnets. This allowed them to integrate the ECD into the frames of the character pieces and, cleverly to use the magnets to conduct electricity, triggering the interaction. Two metal conductors were connected to a battery pack so that when the character pieces are correctly placed onto the frame, electricity will be conducted from the bars through the magnets into the ECD displays. The designs for their character pieces consisted of silhouettes of each character's lower, middle, and top part. Each display contained pieces comprising two complete characters and each character would be fully visible only if all game pieces were oriented correctly. Incorporating multiple characters into their design enabled the team to create an

interaction that enables the user to do exploration and remixing of the characters, until they find and orient all the pieces for one full character. Although this artifact did not use any advanced electronics or programming, the students still managed to create an ingenious, interactive solution that utilizes the unique capabilities of ECDs.

The *Spider-Man* artifact resembled the front of a building with multiple windows that either had static illustrations or ECDs, and two 3D-printed characters that magnetically attach to the frame (see Fig. 4, left). This allows a user to move the characters around on the enclosure and thereby actuate the various displays. By attaching hall effect sensors to the building facade and connecting them and the ECDs to an Arduino, the project team was able to use the 3D-printed characters as interactive objects that switch the displays.

The *Centipede* project team developed a physical representation of an arcade game, using ECDs to indicating where a character is positioned. The user moves this by pressing left or right buttons. Additionally, the team added a "shoot" button which would activate one of the mushrooms in the center part of their artifact (see Fig. 4, right). The *Centipede* project the most complex interactions of all the artifacts, however, most of that complexity comes from the software design and the fact that ECDs can easily be driven and switched by an Arduino.

As described, both *story* and *interactivity* factored heavily into the design of the objects, and shaped both the process and the final outcome. In the next section, we describe how the tools present in a makerspace the ECD technology shaped the fabrication.

4.1.3. Fabrication

In our analysis of how the participants used the equipment available in the makerspace to construct the appearance, functionality and shape of their projects (and in particular, considering the ECDs), we found that groups used a variety of strategies for the way they engaged with the tools, how they found new information, and fabricated their projects. While the makerspace contained a wide range of equipment (laser cutter, 3D printer, CNC machines, embroidery machines, vinyl cutters and more) freely available to the participants, it was only laser cutting and 3D printing that was used, with all participants using laser cutting and two groups using 3D printing. We noticed that the laser cutter became the go-to equipment due to its ease of use and fast learning curve. This might be explained by its ease-of-use but the ready availability of operating instructions on the internet was also a factor. Although all the projects used laser cutting, the manner in which ECDs factored into each design differed.

The *SukiLee* artifact comprised two pieces of laser cut wood which together created a sturdy frame and the perception of depth. Because the ECDs were hanging from the frame on a wire, the participants did not need to create precise measurements. This meant that they could easily design and laser cut the frame without getting hung up on precision (see Fig. 6). This gave the group some freedom, without necessitating multiple prototype iterations and helped them to design rapidly.

The *BugBox* artifact's design similarly did not require a great deal of precision to design its physical appearance, because most of their laser cuts were simple shapes. Although the project's appearance was simple, the team still had to precisely align holes in the moth's wings with metal rods to create a pivoting action. The team engraved one of the wings to contain an outline of the ECDs, and the silhouette of two fingers indicated where the user should place the ECD displays to activate them. They also did not need to carefully take the displays' technicalities into consideration for laser cutting the shape of the box, as they were loosely stored inside it. However, for their engraving they needed to ensure size and shape was the same as the displays they created for the artifact.

The shape of *Spider-Man* is based on a simple construction. The artifact uses finger joints to connect the sides of the box to other sides. This required the group to independently research how to design such joints and instead of manually designing the joints, they used online tools to create them. As the project used several ECDs, the participants had to take into account their sizes and shapes during the design phase.

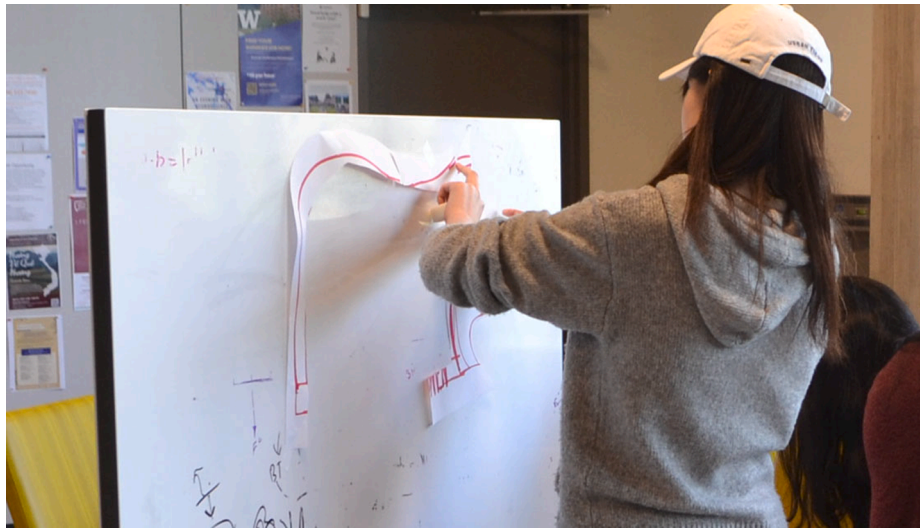


Fig. 6. Participants brainstorming dimensions and shape for the SukiLee artifact.

Also, because ECD displays are transparent and do not have their own source of illumination, the team had to consider how to ensure the user could see the prints them clearly. Additionally, the project contained two 3D-printed characters, which the group modelled and printed themselves.

Similarly, the *AlitoLamp* artifact used finger joints to connect the pieces, the project team used a non-rectangular shape, which required them to research how to ensure the joints would properly connect. Because they had to stack inkjet-printed graphics with ECDs to give the illusion of a moon buggy traversing the moon, they had to consider how this stacking affected the look of ECDs and the size requirements for the lamp panels. This artifact also used 3D printing, however, in contrast with the *Spider-Man* artifact, this group found a model of a joystick online and modified it to their needs before 3D printing it.

The puzzle interaction of the *MixIt-Up* project required laser cutting several pieces that would fit together without getting stuck, in contrast to other teams' finger-jointed designs. In this design, the team had to take into account how to integrate the displays into their puzzle pieces. They did this by creating the frame of each pieces in just the right size to integrate the display, while still providing sufficient room to attach the magnets. The group also had to take into account that the user should be able to pickup the pieces while being able to place them in two orientations and on two sides. To create this, they needed to ensure that the magnets could be embedded into the frames while taking care that the frame could still support the placement and removal of the puzzle pieces. Additionally, their design used multiple layers of laser cut wood to create the depth required for the interaction. The design was visually enhanced with decorative engraving.

The *Centipede* artifact is the only one that uses a combination of paper crafts, laser cutting, and irregular shapes for the ECDs. The enclosure of the artifact itself is designed using finger jointed connections. Carefully cut craft paper pieces are layered together to create the illusion of depth. The team designed and cut the paper with the ECDs in mind, wanting to create displays with a mushroom shape to symbolize the shootable items. To give the impression of a movable character, the team arranged three ECD displays in the enclosure surface. Although they did not need to create high precision cutouts for these character displays, the team still leveraged the ability to create displays with irregular shapes in their overall design.

4.2. Learning Context

To answer our two last research questions we look to the learning context. The fabrication workshop took place in an environment

comprising both the structural learning activities as well as the situated context created by the link to the Atari women.

4.2.1. Structured Learning

The structure of the five-day workshop was designed as project-oriented and student-guided, in accordance to Papert's constructionism. While each day had a theme and an objective, the way in which the participants chose to engage with the theme and reach the objective was flexible. That did not mean that we took a laissez-faire approach but that we followed the participants ideas and curiosity. We supported them through supervision of design, concept, tools, technologies and fabrication aligned with the participants needs and interests at certain times in the project. It was entirely up to the participants how they spend their time, as long as they were working towards the objective of the day. Other required information (e.g. information on how to use the laser cutter, its safety instructions, and digital design requirements) was provided as needed. This approach allowed the participants to have information fresh in mind when working with the equipment. After these short ad hoc introductions, the groups used the equipment and asked for additional support if needed. Having this freedom to work as they saw fit and use the machines as they needed produced an engaged and self-driven environment which the participants particularly valued:

"I did not expect as much freedom as we had with our group, which I really think was helpful for our design critique and creativity." (Participant #8)

"I think I learned a lot more from having the flexible schedules and design freedom." (Participant #11)

While this teaching approach required much more from us, the teachers, in adapting all interaction to individual groups, it also produced a very engaged and self-motivated learning situation that was important for the participants' learning process. The semi-structured and flexible workshop allowed the participants to engage their agency and self-guided learning. For example, participants were asked to identify three ideas for stories about Atari women and collect additional data about their ideas on the first day of the workshop. The purpose was for them to argue their design choices by forcing them to ground their decisions in data, while still keeping the process open.

Although we requested the teams come up with three ideas, it was up to groups to select, based on their data, which idea had to be prototyped. Also, we did not restrict the participants to particular equipment or materials except for the requirement to use ECDs. Making the participants use the equipment themselves, with minimal guidance, resulted in

a lot of learning by failing, which they found positive as can be seen in the following quote:

“What surprised me the most was the structure of the DRG [i.e., the workshop]. In general, the structure of the DRG was much more self-guided (group-guided?) than what I would have anticipated. The hands-off approach allowed for more mistakes and more creative freedom, which I enjoyed.” (Participant #13)

A core part of the workshop was for the participants to use ECDs, which in personal fabrication is a novel process; not much learning material can be found on the internet. Nevertheless, each group learned to design and fabricate ECD displays with a variety of teaching materials (e.g., written instructions, power-point presentation, live-demo, and instructional videos). Because the students did the fabrication themselves, they encountered the technical challenges that would then in turn inform their designs for their projects. This openness to use the makerspace equipment as they saw fit after their first introduction and the goal of creating a fully-functional project was also very positive as can be seen in the following quote:

“I experienced a lot of ‘firsts’ for example, first time using laser cut, first time making the ECD displays, first time attending DRG and learned a lot from everyone. I learned from ideation to prototype and to the actual project, every single stage need a lot of ideas and work. I am so appreciative that I can have this wonderful experience.” (Participant #6)

4.2.2. Relatable Context

We found that because the participants could relate to the context of hidden women in tech and had to create an artifact that brought to light those women encouraged and motivated them to do more. Analyzing the qualitative data from the questionnaires we found that the meaningful and relatable context, which we refer to as *situated learning context*, was crucial for the experiences of the participants.

The majority of the participants (16 of 18) were women and many themselves they could relate to the idea that we are looking at the hidden life of women. Further, they were also interested in Engineering and games. They used those interests and personal experiences as part of their design process. For example, the participants who created *Centipede* embedded their own experiences of micro-aggressions into their project and therefore had experienced similar stigmas as those of for example, Dona Bailey, who was represented in the *Centipede* artifact. By making the context of the workshop relatable, participants were motivated to push the limits and give their best as the below quote illustrates: As a majority of the participants were women themselves and worked with or wanted to work in Engineering they had at some point in their lives experienced similar stigmas as those of the hidden women that were the context of the workshop. This relatability motivated several of the participants to not only do more but also research beyond the given material provided by the instructors.

“It made me motivated knowing we were working about the Atari Women but I think it is because I, myself, think of me as a strong woman and knowing that I could bring to light other strong women pushed me to do a little more than if it was going to be men.” (Participant #8)

The meaningful context — allowing participants to explore the Atari women and researching additional material — shaped the workshop dramatically. The role models the Atari woman presented, whom the female participants could relate to, served as a motivational factor as well as a basis for the content of the artifacts. Several groups chose to initiate independent research into the games made by women in terms of gameplay, design, and interaction features. A few groups that chose to research further did so to find details about the games the women had developed that were not previously known to us. For example, the *MixIt-Up* team uncovered new information about gameplay and graphics of the *Strawberry Shortcake* game developed by Dawn Epstein. This then

informed them about how they meaningfully could utilize ECDs in their artifact. By providing relatable context and content, the participants were driven to figure out how to combine it with the technology as illustrated by the following remark.

“When we were told to combine the stories of the Atari women with the technology, I thought it would be an interesting design challenge. I was motivated to figure out how to tell someone’s story without words and through their own accomplishments.” (Participant #11)

The relatable learning context encouraged the participants to engage in a deeper understanding of the affordances and constraints of the ECDs. This in turn allowed them to successfully design and fabricate functioning artifacts that each told a story about the hidden women developing games in the 1970s.

4.2.3. Extrinsic Motivation

Giving the participants the goal of exhibiting and presenting their artifact at a later time outside of family, friends and university (*extrinsic motivation*) excited them to push further and increase their engagement. This is, for example, seen in multiple groups painting their artifacts to give them a more finished look. And the teachers experienced multiple days where groups wanted to stay later than the planned time of the workshop to have enough time to reach their goal. Also having to exhibit an artifact with subject of meaning to the participants was very positive to the participants as seen in the following quote:

“I had no idea what our main goal was going to be with this research group, but when I found out that we were going to present artifacts that we made for women, I was more than ecstatic.” (Participant #8)

Another consequence of having a goal beyond the workshop was that several participants expressed they wanted to continue working on their artifacts after the workshop ended. Their motivation was such that they specifically requested out-of-hours access to the makerspace to continue their work. Here we observed, that the students did not only work towards getting their credit points, but actually developed intrinsic motivation and reflecting on what could be improved to ensure they had the optimal artifact for presentation as seen in below:

“I am certainly planning to continue working on it. I showed some pictures to friends and family, who were very receptive and interested. I want to finish mounting the display and lock the wiring in place to hopefully reduce issues later on. I could also see updating code to make it more intuitive to use and see screen changes on. I want our project to look as good as possible for its final presentation.” (Participant #2)

5. Discussion

We now turn to a discussion of the results of our work, and provide suggestions for introducing new technologies to the makerspace repertoire. Our findings suggest guidelines that fall into three main categories:

- Participant motivation
- Design framing and relatability
- Support to explore and fail, especially with novel technologies

With respect to our research question, “How does a public exhibition impact participants’ learning outcomes?” it became quite clear that having the artifacts live beyond the workshop and having to present them at a museum to people other than friends, family and people at the university had a significant impact on the learning outcome. It served as *extrinsic motivation* and was essential for the workshop participants, as it created a meaningful context for their engagement and encouraged them to produce detailed and well-developed artifacts.

The *extrinsic motivation* was shaped by the planning of an external

event, the exhibition at the museum. The students cared how their projects would be read by the general public and wanted to ensure that the stories of the Atari women were understood. While an exhibition could also lead to a certain level of pressure which might counteract the participants' motivation, we did not find any evidence for this here. It is of course, not always possible or feasible to stage an exhibition of work, and it might also not be practical for all maker workshops. However, we recommend that facilitators of such workshops ensure that its work products can be easily shared with others outside of the makerspace, for example through pictures and videos, or social media as suggested in [48], at a minimum. While sharing in itself is not novel to constructionism, our findings validate that it is also important for early University students and that having to share the work outside of the makerspace further adds to the motivation of the participants.

Moreover, because the participants could relate to the historical figures, and felt these histories were of personal importance to them, they devoted extra effort to creating artifacts that would do justice to those women. This contributed to our question, "*How does using Atari Women as the design framing impact that participants' learning context?*". Giving participants relatable stories and role models substantially increased their personal motivation. This is in accord with the findings of Mellis et. al., who showed that individual goals and scope are important for personal fabrication [49], and also the work of Aronson and Laughter [50].

This increase in motivation was also evidenced by the fact that most groups initiated their own research and sought both contextual/historical and technical information not provided by the workshop facilitators. We set the stage, but they drove their own inquiries, and we allowed them the space and time to conduct their research. For our approach to be adopted elsewhere, facilitators should ensure that their teaching materials and learning environment will support participants finding more information independently, and ensure time for this. We did this by incorporating dedicated design session into the workshop in which participants ideated several concepts, gradually narrowing down to the core ideas they wished to communicate with their projects. This was further supported by the latitude to freely use the variety of different resources, technologies (in our case, ECDs), fabrication tools, and other equipment available in makerspaces.

Again, we acknowledge that it might not always possible to find a suitable learning context, with relatable role models such as the Atari women. However, prior work has shown that when facilitating such workshops, not only are the individual learners' goals important for the learning outcome, but also that *imagination and fantasies* (evoking images of objects or situations not present) represent a key ingredient of effective (and fun) learning [51,52]. Besides using actual historical events as design framing, we suggest that another strategy might be to repurpose relatable fictional stories.

Our first research question focused on the specific characteristics of the novel display technology we used in the workshop: "*How does the limitations of the ECD technology influence the design activities in the makerspace?*". We found several elements that highlight the challenges and opportunities of ECDs.

One of the unique features of ECDs is that they can be fabricated in irregular, arbitrary shapes, using ink-jet-printed graphics. This means that our participants could create relatively complex graphics controlled by simple technology (i.e., a simple 1.5 volt AA battery or basic microcontroller, such as Arduino). Other low-voltage displays require much more complex display driving circuitry. All participant groups exploited this by creating detailed graphics embedded into their projects, which meant they each had a fairly detailed user interface which worked, even though the participants did not have a lot of programming experience. Apart from this, we also noticed that using ECDs resulted in projects that were not confined to the common understanding that display screens are rectangular. Several artifacts used displays that were not uniform, such as the *BugBox* project's triangular displays and the *Centipede* artifact's mushroom shaped displays.

Perhaps the most remarkable outcome leveraged another unique feature of ECDs: the printed graphics can be made invisible. A few of the projects used this to accentuate the story surrounding the Atari game developers, or the game itself. This is especially seen in the *SukiLee* project, in which the participants used invisibility to demonstrate how these women programmers were *historically and culturally invisible*. Their work leveraged the novel technology to articulate and accentuate one of the key aspects of the historical narrative of the women Atari developers: to most people, they did not exist. This interpretation was a powerful expression of the group's understanding of both the historical context of the workshop's design framing and the capabilities of the ECD technology.

We observed that the constraint of not being able to change the graphics after fabrication meant that the groups had to thoroughly think through their design. Design constraints often lead to novel work-arounds. This further meant that what participants focused on had a big impact. The inherent technical limitations of the displays (e.g., cycle time, vibrancy of graphics) limited what it is possible to present in the displays. This required the groups to sharpen their analysis and overall story of the artifact.

We believe ECDs show promise for experimentation and novelty in participatory workshops because they are easy to fabricate but at the same time have a large potential for expression (low floor - high ceiling). However there are certain elements for improvement. Previous work reports that ECD technology is robust [15] which holds true when fabricated and used correctly. Nevertheless, unexperienced makers can fall into several pitfalls that might not be immediately self-explanatory to them. Several groups experienced burnt displays due to either not UV curing them properly or powering them with a too high voltage for prolonged periods of time. Compared to a laser cutting process, where burn marks can be easily explained by either using too much power or too low speed this does not extend to ECD technology. The interplay of electronics and the chemical process in ECDs make them hard to understand compared to other maker technologies. Here specific electronics driver boards for the displays that contain logic for driving displays without damaging them could be used. However, this would also limit what the participants are able to explore with the electronics and therefore also their exploration options during the workshop.

While mistakes can be an efficient and memorable experience for learning, it is only valuable if explainable, which is not necessarily a given with ECDs. The right amount of support is critical. We found that it is important to provide participants possibilities to explore and fail. Too much guidance hinders one of the most positive characteristics reported by participants, that is, the latitude to creatively address problems. It is also important to develop teaching resources tailored to the sweet spot that provides "just enough" learner support. Effective teaching materials should also communicate potential failures, explaining not just what to do, but also "what not to do", with examples of fabrication errors and the failures that result. As [12] report, there is more work to be done on how to make effective maker instruction material. Another pitfall of ECDs is that designing displays with optimal switching capabilities requires balancing the amount of ink on both sides of the displays. Optimal designs should have balanced areas of electrochromic ink that are activated or deactivated. Our participants had to do this by either guessing or fabricating and hoping they had a balanced amount. Simple software tools that can indicate whether or not the graphics for the two sides are balanced in ink amount can improve robustness and lifespan.

This work contributes in several ways to future designs of maker-space driven workshops. Having a guiding theme, that the participants can relate to drastically increased their engagement. The extrinsic motivation of the exhibition sparked further motivation as well. We demonstrated that novel technologies (ECDs) can be easily integrated into the process as well, but also laid out several pitfalls that might arise from this. While we specifically focused on ECDs, the findings with regard to learning can also be applied to other novel fabrication techniques. To summarize into points lecturers and facilitators should

consider when facilitating workshops with new technologies:

- **Relatable Guiding Theme:** Facilitators should provide relatable role models where participants are tasked with researching their background and history to find relevant information for the workshop outcome. Where this is not possible we propose repurposing relatable fictional stories that participants can identify with.
- **Extrinsic Motivation:** Arrange an event where participants have to share their work outside the makerspace. We used an exhibition to great success but where this is not feasible we recommend makerspace facilitators set up other forms of extrinsic sharing, e.g. in the form of social media stories or videos.
- **Introducing Novel Technologies:** Bringing new technologies into the makerspace should allow exploration and failing while teaching materials provide both what to do and what not to do. The materials should also provide examples of errors and what caused them so it can be backtracked to where in the process something went wrong, similar to e.g. how the 3D slicer software Simplify3D provides a print quality troubleshooting guide.¹

6. Conclusion

We presented the results of our exploration into how creating an interactive artifact in a fabrication workshop can teach participants to work with a new technology, in this case electrochromic displays. We ran a week-long workshop with a follow-up exhibition at a museum. We have shown that using *structured learning*, a *relatable learning context* and *extrinsic motivation* increases both motivation and engagement in participants and allows them to both design and fabricate ECDs. Through the workshop, six artifacts were fabricated by the participants and later presented at the museum. Although all groups were able to design and fabricate displays, we found that ensuring the makerspace had all the tools required ready to use was important to avoid failures. Additionally, we found that teaching material should not only show the correct process but also what happens if that process is not followed. These findings are summarized into three points that lecturers and facilitators should consider when introducing new technologies in a workshop setting.

For future work we aim at running similar workshops but with a different target demographics e.g. creatives that are in their mid twenties and are not attending school. Besides this, we also aim to run workshops with different new technologies that reach a state where they can be used in a setting similar to how ECD's were used in this workshop. Running these workshops with those new technologies will allow us to investigate whether the findings apply there as well. Furthermore we want to explore what kind of extrinsic motivation elicits the most motivation and engagement, are video presentations as effective as a physical museum exhibition for example? Also social media stories could be an option, as they would for example increase the extrinsic motivation to demonstrate ones capabilities in front of friends and family members.

While this teaching approach required much more from us, the teachers, in adapting all interaction to individual groups, it also produced a very engaged and self-motivated learning situation that was important for the participants' learning process. The semi-structured and flexible workshop allowed the participants to engage their agency and self-guided learning. For example, participants were asked to identify three ideas for stories about Atari women and collect additional data about their ideas on the first day of the workshop. The purpose was for them to argue their design choices by forcing them to ground their decisions in data, while still keeping the process open.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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