Dispray: The Design of an AR-Augmented Airbrush for Electroluminescent Display Fabrication

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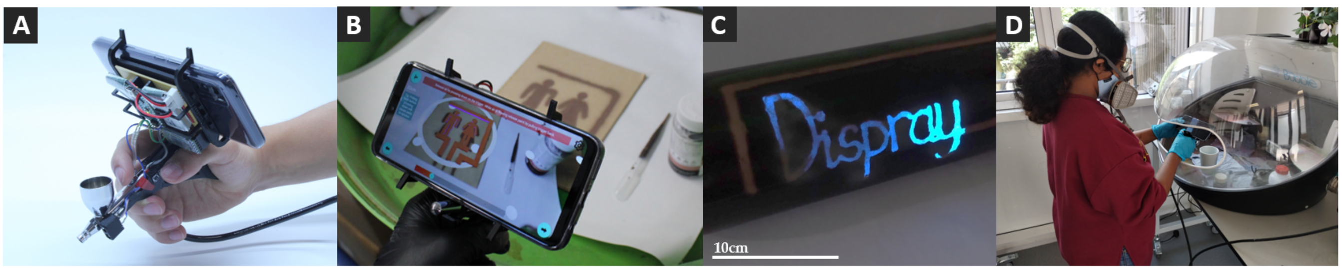

Figure 1: To overcome barriers in designing and adopting bespoke fabrication tools, we collaborated with artists and engineers to iteratively develop (A, B) Dispray - an augmented airbrush with embedded assistive technology and AR guidance that supports learning to spray electroluminescent materials. (C) We demonstrate the tool's functionality through interactive applications such as signage on a bottle. (D) We evaluate our design process through interviews and walkthroughs with original stakeholders and assess the tool's effectiveness in a multi-session learning study with novice users.

ABSTRACT

Recent advances in material-centric personal fabrication have enabled the use of custom inks and paints with functional properties to create free-form displays. However, working with these materials, such as through airbrushing, remains a skill-intensive process that limits non-specialist access, adoption, and further development. To address these challenges, we developed Dispray, an AR-augmented airbrush tool for fabricating electroluminescent displays. The tool was shaped by insights from a study with artists and engineers and refined through iterative prototyping. We evaluated Dispray by re-engaging with the original artists and engineers and conducting a follow-up study with novice users, demonstrating its effectiveness in supporting both skill acquisition and functional fabrication. This work contributes a novel approach to connecting emerging material fabrication with accessible, user-centered tools, advancing the democratisation of interactive device creation.

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CCS CONCEPTS

• **Human-centered computing** → **Displays and imagers**; *Walkthrough evaluations*; *Ubiquitous and mobile computing design and evaluation methods*; • **Hardware** → *Tactile and hand-based interfaces.*

KEYWORDS

Personal Fabrication, User-Centered Design, Tool Design, Electroluminescent, Airbrush, Display Fabrication, Speculative Stakeholders

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1 INTRODUCTION

Personal fabrication within the field of HCI has advanced significantly in recent years. This progress includes novel fabrication methods, many centered on manipulating active materials [4, 21, 63]. More specifically, numerous works are now investigating material-centric personal fabrication as a way to create **free-form displays**

[23, 27, 49]. For example, a range of works explore disparate display materials such as electroluminescent (EL) [55, 90, 91], electrophoretic [22] and electrochromic structures [39]. These works also propose various deposition methods such as screenprinting [55], spraying [28, 89] and hydroprinting [20].

However, prior research has highlighted the complexities and diverging approaches in the material-centric fabrication of displays [21]. In the context of personal fabrication this is particularly prohibitive to the non-specialist maker. Working with inks that require precise deposition and complex handling presents significant challenges. Makers must engage with a broad range of technical knowledge, raising barriers to entry and limiting widespread adoption and further innovation. Moreover, the lack of integrated support often forces makers to rely on time-consuming trial and error, which slows development and risks producing structures unfit for practical use. To accelerate progress, there is an opportunity in developing supporting tools that embed domain expertise, assistive technology, guidance, and teaching features. We argue that such tools are essential to address the inherent complexity of advanced material-centric fabrication processes.

To demonstrate the design of a tool for fabricating free-form displays, we present a series of studies that have shaped the design, development, and evaluation of Dispray, an AR-augmented airbrush tool to support spraying electroluminescent (EL) materials. Dispray enables users to engage in the complex process of spraying layered materials to create effective free-form displays. By providing real-time guidance and learning support, Dispray lowers the barriers posed by the domain-specific knowledge and precision typically required for this type of functional fabrication [59, 88, 92].

We focus on the case of spraying EL materials [9, 90] because of the versatility of this technique. EL has been shown to be directly manipulable by makers through accessible tools and materials, such as in PrintScreen [31, 55] as well as promising application to non-planar surfaces such as in Objectskin [20] and ProtoSpray [23]. Furthermore, EL materials deliver functional advantages relative to other display materials, including higher refresh rates, improved visibility, greater reliability, and structural simplicity [27, 28, 37, 89].

By exploring the design and evaluation of Dispray and more generally spraying active materials, we hope to pave the way for more accessible, skill-bridging tools which can empower a wider range of makers to engage with advanced material-centric fabrication processes. This work aims to inspire future research and development in assistive technologies that will not only lower barriers but also foster creativity and innovation in personal fabrication.

This work makes the following contributions:

- Design insights for developing a tool to spray EL materials for the purpose of free-form display fabrication, derived from a study with 12 stakeholders (artists and engineers).
- A design space derived from stakeholder insights, developed through low-fidelity prototyping and iterative exploration, culminating in the concept of *Dispray.*
- A high-fidelity implementation of *Dispray*, an AR-augmented airbrush tool.
- Feedback on the usability and applicability of the Dispray tool, as well as its potential for integration into real-world practices, derived through a study where we re-engaged in-person with the original artists and engineers.
- An exploration into *Dispray's* capability to support learning and independent fabrication with the outcome of the tool being positioned as both a teaching aid and an accessible tool for engaging with EL spraying. This exploration involved carrying out a follow-up study with 4 novice users, each using Dispray in three 1-hour sessions and additionally completing three 30 to 45 minute interviews.

2 RELATED WORK

2.1 Active Materials in Personal Fabrication

The integration of active materials into personal fabrication has opened new opportunities for creation of interactive devices with novel form factors, enhanced functionality, as well as the potential for automated production [4, 52, 63]. DisplayFab differentiates material-centric methods from component-based personal fabrication processes, contextualised with convergence of material-centric input sensing and the divergence of material-centric digital output functionalities [21]. We draw from the roadmap the need for tools that lower barriers for non-specialist engagement to enable adoption and further development. Within the space of input sensing, manipulation of malleable [69] or fluid material [11, 94] has allowed work to explore the fabrication of free-form sensing structures. Automation of these processes has enabled significant work towards on-demand creation of custom interactive devices. 3D printed conductive traces allow for capacitive sensing through rigid structures with programmable creation of form factors[7, 72]. Extensions to this work enable 3D printing of deformable materials through resistive sensing [67]. Further work extends the concept of automated deposition to hand-held devices with Pourjafarian *et al.* [60] introducing a hand-held printer to layer on conductive material as sensing patterns and Klamka *et al.* [32] exploring ironing as a fabrication method. These works contribute to lowering the barrier to entry for fabricated interactive devices through custom self-contained handheld tools.

Personal fabrication of material-centric displays was first introduced in PrintScreen [55], expanding the form factors of electroluminescent (EL) displays through a fabrication method presented covering screen- and inkjet- printing. This project has been extended into the space of programmable paper by Klamka *et al.* [31], exploring the potential for an EL research platform to enable exploration of fabricated digital surfaces. Objectskin allows layering active materials on irregular topologies through hydroprinting [20]. ProtoSpray and Sprayable User Interfaces [23, 90] introduced deposition of active materials through spraying. Wessely *et al.* showed the benefits of spraying active materials for irregular topologies using projection and computer generated masking to guide deposition. In ProtoSpray, Hanton *et al.* show these methods can be used to integrate active material deposition with the benefits of programmability and object creation through multi-material 3D printing. This is further extended by Child *et al.* who support explorations of sonolithography including EL electrode patterning [9]. Development of novel EL manipulation such as stencil-less solutions and using conductive 3D printing lower the barrier to entry for the whole EL fabrication process. However, these methods still rely on a user's manual handling of EL spraying and as such have a fundamental baseline of user domain knowledge, leading to a need for tools that support non-specialist learning and fabrication. EL offers rapid refresh rates and applicability to a range of surfaces, meanwhile the Decochrom project [5, 27, 38] has explored the use of electrochromic (EC) material through a combination of craft and programmable methods such as inkjet printing. Other works further extend this divergence of both material type and application process. Zhu *et al.* explore the portability of activation systems for photochromic materials [97] extending the explorations of handheld devices to span the gap between craft-based fabrication and automation. Zhu's work further extends existing work laying the foundations for photochromic as a digital output fabrication material [24, 28, 62, 89]. In recent advancements exploring automated fabrication, Moon *et al.* develop processes for building custom structures of thermochromic material [49] extending prior work on thermochromic materials [58]. Meanwhile, Hanton *et al.* employ unconventional upcycling and make the argument for the optimal properties of E ink, and its potential within personal fabrication [22]. Due to its early stage of development, a significant focus of active material fabrication is on the development of novel methods with limitations regarding consideration of the user at the center of personal fabrication [21]. This paper is motivated by the need to take complex fabrication processes that are on the edge of personal fabrication and explore the extent to which these can be made available to non-specialists, through supporting each stage of complex fabrication methods and the long-term development of non-specialists domain knowledge.

2.2 Tool Design for Personal Fabrication

Many projects look beyond active materials to create personal fabrication tools that support adoption, introduce new fabrication processes, and connect existing maker practices with emerging approaches. In "Drill Sergeant", Schoop *et al.* [73] apply software methods, instructional workflows and guidance to non-smart tools. In a recent exploration, Adroid [81] uses projected AR and a robot arm to support analogue craft-based fabrication tasks. Knibbe *et al.* [33] explore a smart maker space with embedded domain knowledge for tools and DIY processes. For specific tools, in Turn-by-wire Tian *et al.* [82] proposed a lathe with integrated haptics, and while turn-by-wire explores interactive design, it's design process is not explored in depth. FreeD [98] looks at a mixed control milling set-up with computational input and handheld control from the maker. Takahashi *et al.* [80] combine a 3D pen and 3D printer to prefabricate skeleton structures for rapid prototyping. Similarly, in ProtoPiper [1], Agrawal *et al.* explored a single handheld tool for rapid prototyping integrating it into 3D design itself. Extending the focus on contained handheld fabrication tools, Roumen *et al.* [66] explore mobile fabrication with human assisted handheld lasercutting. In River's *et al.*'s work [64] they explored error correction within real time fabrication within 2D settings. Further explorations extend these concepts to span interactive fabrication, the process of continuous or turn taking real-time intervention in automated fabrication processes [92]. In "Interactive Construction" [54], Mueller *et al.* develop a system for interactive lasercutting and drafting. While Reform [87] researches how the flow between digital input and physical output can be made bidirectional with real time changes. Fossdal *et al.*'s work [17] explores extending interactive fabrication to craft based practices for glass-work. These works develop and underpin themes of compactness and self-containedness within tools, as well as exploration of hybrid guidance enabling creativity with computational support.

Recent work explores the intersection between fabrication methods that can enhance creative expression such as clay 3D printing and computational processes [51]. In SculptAR, Passananti *et al.* explore direct manipulation of material through AR [57]. Devendorf *et al.* explore the design of interactive systems through artist residencies [13], while Friedman-Gerlicz et al. employ this approach to develop a step-change slicing tool [18]. Meanwhile, Bourgault *et al.* address the core intersection of how digital fabrication and craft practices can intersect [6]. The development of personal fabrication tools, engagement with maker-culture and integration of user-centered design principles provide foundations for the tool development necessary to enable adoption and development of active material fabrication methods. There is currently a gap in existing research of explorations into tools that support the personal fabrication of interactive devices, especially for material-centric fabrication methods.

2.3 Computational Spraying Tool Development:

Beyond HCI, many studies investigate computer controlled spraying for art and functional coatings, mainly using traditional paints, from handheld methods to fully automated systems, examining spray deposition automation. Vempati *et al.* introduce "PaintCopter" [85], a spraying drone extended to a multi-drone set up by Uryasheva *et al.* [84]. The PICARSO project introduced a wall-mounted spray system [26], while Elsdon *et al.* develop a way of combining computer controlled motion with a handheld device [16]. Luk *et al.* introduced a tool for digital expression via spray paint [42], meanwhile Shilkrot *et al.* developed a 6 DOF system using camera tracking to support 2D design, limiting paint flow relative to the maker's hand's position [76]. Prevost *et al.* used webcams to track a spray can whose nozzle can automatically deposits material [61]. Further works explore fully automated spraying in academic [26, 47, 74, 79], industrial [14, 86, 96] and non-academic artistic [29, 83, 93] contexts. We draw inspiration from these works in the context of a technical augmented airbrush but we note that these projects focus on non-active materials. We identify that while these works span broad system types and implementations, none explore either active materials or the precision needed for finely controlled conductive traces compared to manual airbrush manipulations [35, 90].

3 METHODOLOGY

We provide an overview of our approach, explain our qualitative data analysis and participant selection, and detail each experimental setup in its respective section.

3.1 Research Questions

We evaluate the following research questions to explore the fundamental questions around designing a handheld tool for EL display fabrication:

RQ1: What are the design parameters for creating a low-cost, compact augmented tool to support active material fabrication through EL?
RQ2: How effective is the Dispray high fidelity prototype in supporting both users' learning and their ability to enact active material fabrication?
RQ3: What is the scope for adoption of active material processing from participants?

3.2 Overview

We use a user-centered design approach to incorporate diverse perspectives and address challenges such as understanding maker experiences, handling technical complexities, and considering real-world usage contexts. This is especially important given that the area is still not widely adopted. We employ qualitative methods and work closely with groups of participants to capture the subtle nuances of individual maker perspectives and the contexts in which design and fabrication decisions occur. This approach aims to create a more inclusive, intuitive, and effective tool [78], ultimately supporting broader adoption and ongoing development.

Step 1: Our first step is a study with 12 stakeholders to guide the design of a tool for spraying EL materials, aimed at enabling the creation of free-form displays (Study 1).

Step 2: After analyzing the feedback, needs, requirements, and ideas gathered from step 1, we define a design space for the tool. This process involved low-fidelity prototyping and further gathering of informal feedback from novice users, eventually leading us to converge on the concept of the Dispray tool.

Step 3: We then implemented a high-fidelity version of Dispray which uses AR techniques combined with an airbrush.

Step 4: We re-engaged with the original stakeholders in a new study to gain deeper insights into its usability (Study 2). We were able to gather feedback, through in-person walk-throughs and 1:1 interviews, not only on the tool's design and functionality but also on its broader applicability, limitations, and potential for integration into real-world practices.

Step 5: We followed this with a further three-day study (Study 3) involving novice users to evaluate how effectively Dispray supports learning and independent use of EL spraying, assessing its potential as both a teaching aid and an accessible fabrication tool. Each day the users spent 1 hour working with the tool under observation and then gave their perspectives in a 30-45 minute interview.

3.3 Participants

3.3.1 Stakeholders: For Steps 1 and 4, we recruited 12 participants divided into: 6 engineers (2 women, 4 men; P1–P6) specializing in 3D printing and engineering, and 6 artists (4 women, 2 men; P7–P12) specializing in novel materials and their applications. These specialisms were chosen to reflect the overlap of personal fabrication and artistic methods relevant to display creation. Participants were recruited via email, word of mouth, and posters, with clear communication of required expertise and an overview of EL spraying, emphasizing curiosity about its function and potential. Figure 2 shows the distribution of expertise. Among the engineers, we recruited a student who 3D prints as a hobby, a technician for an Optomec 3D printer [56], two founders of fabrication-related startups, an electronics specialist, and a material science researcher. The artists comprised one full-time mixed-media artist, two full-time painters interested in spray techniques, two part-time painters/hobbyists, and a graphic designer. All participants had experience with adjacent technologies (3D printers, electronics prototyping, or spraying tools), but only one (P5, the materials scientist) had prior experience with EL materials. Participants received a £10 voucher and £15 more if they participated in step 4.

3.3.2 Novice Users: For Step 5, we recruited 4 novices (2 women, 2 men; P13–P16) to explore the process of learning EL technology from scratch. Participants self-reported having no background in 3D printing or the arts, although several expressed prior interest in the technology. All participants provided informed consent and were free to withdraw from the study at any time. They received 30GBP each.

3.4 Data Analysis

We collected written responses from all participants, notes taken by organizers and interviewers, and transcribed audio recordings. To analyse our qualitative data, we employed mixed methods. In our initial study (Step 1), we used content analysis to identify the criteria participants wanted to see in the system, as well as to highlight their ideas and constraints. This helped us group the key requirements and expectations for the tool. In Steps 4 and 5, we used thematic analysis [10] to gain a deeper understanding of participants' feedback and the contexts in which the tool might be used. After reviewing the material, two coders independently generated codes, then met to align them for reliability. Codes were grouped into broader themes reflecting shared concerns and ideas, supporting the project's goals of creating a spraying guidance tool while capturing individual maker and artistic perspectives.

4 STUDY 1: DESIGN SESSIONS

We ran design workshops to explore maker perspectives and generate design ideas [15], addressing RQ1 on tool design parameters. Our approach was deductive, focusing on grounding the process in real-world needs and experiences.

4.1 Experimental Set-up

The first workshop was carried out with engineers (P1-P6) and the second with artists (P7-P12). Each lasted 60 minutes including a 10-minute presentation of existing methods in personal display fabrication. We scoped the project as exploring the development of the technology: deposition of EL materials via spray (building on prior work: [35, 68, 90]). We thus presented an overview of EL technology, and the use of an airbrush as state-of-the-art in the personal fabrication of displays.

We used Zoom and a shared Miro board [48], enabling discursive and visual idea interaction. Remote sessions eased recruitment,

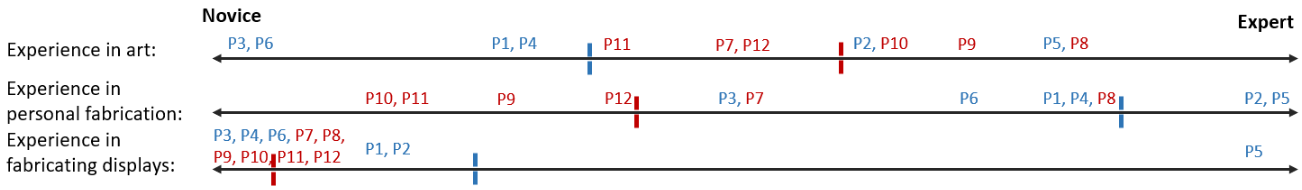

Figure 2: Self-assigned levels of specialism for the stakeholders in two groups: Engineers (P1-P6) and Artists (P7-P12). Averages of each group are indicated by vertical lines.

allowed multiple specialists to join simultaneously, and broadened participation internationally.

The workshops comprised three exercises. First, participants ideated applications for fabricated displays as an icebreaker to explore potential uses, which we do not discuss further, though it encouraged speculation. Second, they examined constraints on the process based on their expertise. Third, they designed an active material spray tool. Below, we present the results of the latter two exercises.

4.2 Results: Constraints Surrounding EL Spraying

Our analysis identified four categories of constraints in EL spraying, described below.

4.2.1 Fabrication Setup: This category encompassed the maker's identity, the location of fabrication, equipment, costs, and substrate preparation for spraying active materials. The maker's skill level and dexterity are key constraints, with P5 highlighting the difference between user and fabrication and P3 noting accessibility concerns for people with disabilities. P1 and P3 raised concerns about *"working in different environmental conditions"* and the need for equipment like compressors (P1, P2). The substrate is crucial for adhesion and conductivity, with P4 noting multiple facets like *"cleanliness, roughness, and adherence."* The high cost of EL materials also limits adoption, with P2 emphasizing cost as *"always a constraint"*. A tool should minimize waste, be portable [66] and accessible.

4.2.2 Fabrication Factors: Constraints on a fabrication process relying on a handheld tool were raised both for limitations regarding the *skill* of the maker including concerns over *"...fine motor skills"* (P3), and *"repeatability"* (P2). P1 and P10 had concerns over the *domain knowledge* required, suggesting that this could be part of the tool design. P10 raised the issue of designing for interaction and how one could preempt what a display would look like. P1 and P3 discussed time taken with P3 raising concerns over *"time and drying... in practice that is a big issue"*.

4.2.3 Display Features: Participants were concerned over fidelity of output with P11 wanting deposition that is "carefully patterned" to display nuanced information. P10 and P3 both emphasised the need for colour displays. P2 and P7 each explored robustness of output display. Regarding *power and control*, P4 notes the constraint of *"safely attaching control"*, while P7 alludes to the need for tool to support connection of power and control.

4.2.4 Display Impact: The final constraint to the fabrication process is the contextual situation and interactions surrounding an end-device. The choice by makers to *actively* display information without consent was discussed by the artists. P7, P12 and P11 highlighted questions around pranks, vandalism and misuse questioning *"How to prevent misuse while still allowing fair use?"* (P11). In contrast to temporary displays raised by P7, P6 explored longevity asking *"how easy is it to repair?"* with P4 raising concerns over *"environmental impact"*, suggesting integration within a tool of responsible use information.

4.3 Results: Tool Requirements for EL Spraying

Stakeholders explored ideas around the input to the tool, the output to the user and specific tool features.

4.3.1 Input to tool: Computational input can be categorised into on-device and off-device sensing, with sensing including camera based visualisation tools and inertial measurement units (IMU) to calculate relative position and movement. Discussion between both groups of participants explored options for system input and output. Here, a split was identified between manual systems, automated set-ups and hybrid solutions. To create a truly interactive computational airbrush, the tool and system require accurate input of factors such as tool position, angle and movement. Users within both design workshops identified a range of different set ups to calculate these factors focused around cameras and sensors with P2 suggesting a combination of both set ups. Suggestions of sensors such as an accelerometer (P11) or full IMU (typically an accelerometer and gyroscope) (P1) were made. P1 suggested a *"Camera that tracks success of painting, can provide data for feedback to user to go over certain areas again"* while P3 promoted *"Capability to scan an uneven surface so that the distance from nozzle to surface is known"*. The exploration of attachment to a robot arm to provide precise location, while technically promising represented a trend with non-contained options where a broader space would have to be developed, arguably going beyond the bounds of personal fabrication.

4.3.2 System output: Computational output can be categorised within a continuum from manual systems and set-ups to automated set-ups going through hybrid features. P6 advocated for a manual

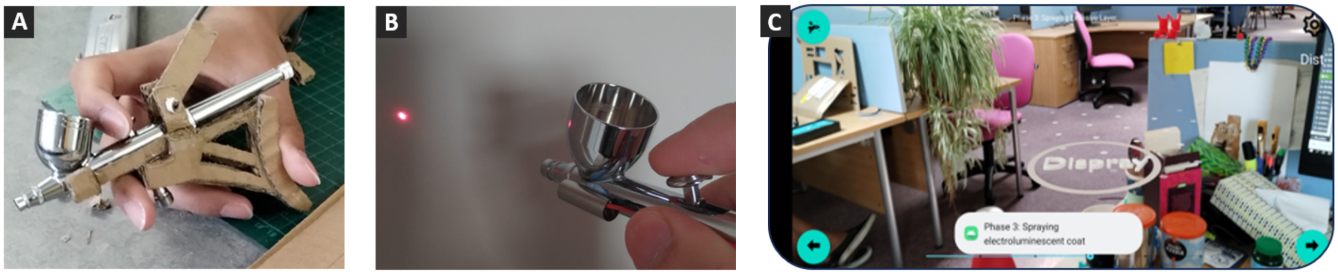

Figure 3: Low- to high- fidelity iterative prototyping: A) an early-stage cardboard mock-up of the Dispray tool to feedback interactive features placement, ergonomics and design of form; B) a low-fidelity test of whether a laser pointer enhances functionality and feedback to user; C) an early-stage prototype of Dispray's AR environment and UI.

tool stating *"it'd just be like a sketching tool...*. Other participants included discussion over guidance systems or automated intervention providing the basis for our system development choices. Within a guidance system, GUIs were discussed with P9 suggesting a *"symbol to show the angle you are spraying"* and P7 suggesting use of an *"AR display with options to change colour and/or design"*. P4, P7 and P6 discussed the use of a projector to guide user's spraying, meanwhile P1 and P4 explored haptic feedback for guidance. On the other hand P1 and P3 advocated for intervention through hand-held gimbles. Meanwhile, P10 and P1 promoted full automation through *"control from afar"* and use of a telerobot. Automation was a common theme in both discussions with P7 suggesting a wall-plotter with a *"roomba-like bot that climbs walls and sprays your design for you on it"* while P4 suggested a set up where we *"fix the spray head and move the part"*. P5 suggested the use of *"ultrasonic sensors... to control the position of the spray nozzle"* [9, 75], building on their specialism (Figure 2).

4.3.3 Specific tool features: Many designs and features were incepted and ideated on by participants. Participants identified the need for the compactness of the system and whether it is formed of multiple devices, engagement with a wider community set up and design transfers. Integrated design emerged as key concept with participants with P9 suggesting *"pre-made designs"* and P3, P7, P9 and P11 each discussing community knowledge transfer in various forms. From a software and design perspective, P11 suggested a quantity/cost estimation. Regarding functional implementations, P1 suggested *"Flow detection, clog detection [and] estimate [of sprayed] thickness"*. P10 and P12 suggested stabilisation: *"Shake control/ correction to make smoother lines"* (P10). P10 also suggested integrating a UV light: *"If [material is fluorescent] could have fluorescent light to help with application"*.

4.4 Summary

This study identified both a range of key constraints and tool design options that should be considered for the Dispray tool (RQ1). Participants highlighted challenges around user identity, skill level, and accessibility, particularly regarding dexterity and technical knowledge. Concerns over portability, environmental conditions, and additional equipment, such as compressors, were raised, with cost seen as a major limitation due to expensive materials. The complexity of material preparation, fine motor control, and replicability were also barriers for non-specialists, underscoring the need for accessible design. The study also highlighted the need for ethical and sustainable solutions. Both artists and engineers were enthusiastic about the potential of Dispray to support innovative uses of EL materials, but their expectations diverged. The artists expressed caution over impact and implementation with questions around expression and breadth. The engineers provided a broader range of technical solutions but a narrower scope of constraints.

5 CONVERGENCE OF DISPRAY TOOL DESIGN

The first study produced diverse design suggestions, leading to many possible fabrication tools. We describe how we refined these into the final high-fidelity Dispray tool, drawing on 1) related technologies, 2) iterative prototyping, and 3) six years of experience with EL technology, including teaching seven students in PhD and Masters projects.

5.1 Morphological Chart

Figure 4 shows our morphological chart [8] of suggested features for building an augmented airbrush tool. We developed it from our workshop results, drawing on constraints, tool design themes, and specialists' technical suggestions to shape the tool's potential form. We also drew concepts from the related literature as it provides additional knowledge about the bounds of what is achievable through spraying systems. First, we cover the design directions for tools derived from the design workshops under the categories 1) Input to tool, 2) System output and 3) Tool features, synthesised through the lens of related work. We then explain the choices made for the Dispray prototype presented here. While we grouped artists and engineers separately to be able to juxtapose differences in their perspectives, ultimately we weighed their suggestions equally.

5.1.1 Input to Tool: Computational input can be categorised into on-device and off-device sensing, with sensing including camera based visualisation tools and inertial measurement units (IMU) relying on accelerometers and gyroscopes to calculate relative position and movement. Existing works track the position of the spraying and record deposition of the system in different ways. Some works use contained systems with positioning functions (a wallplotter

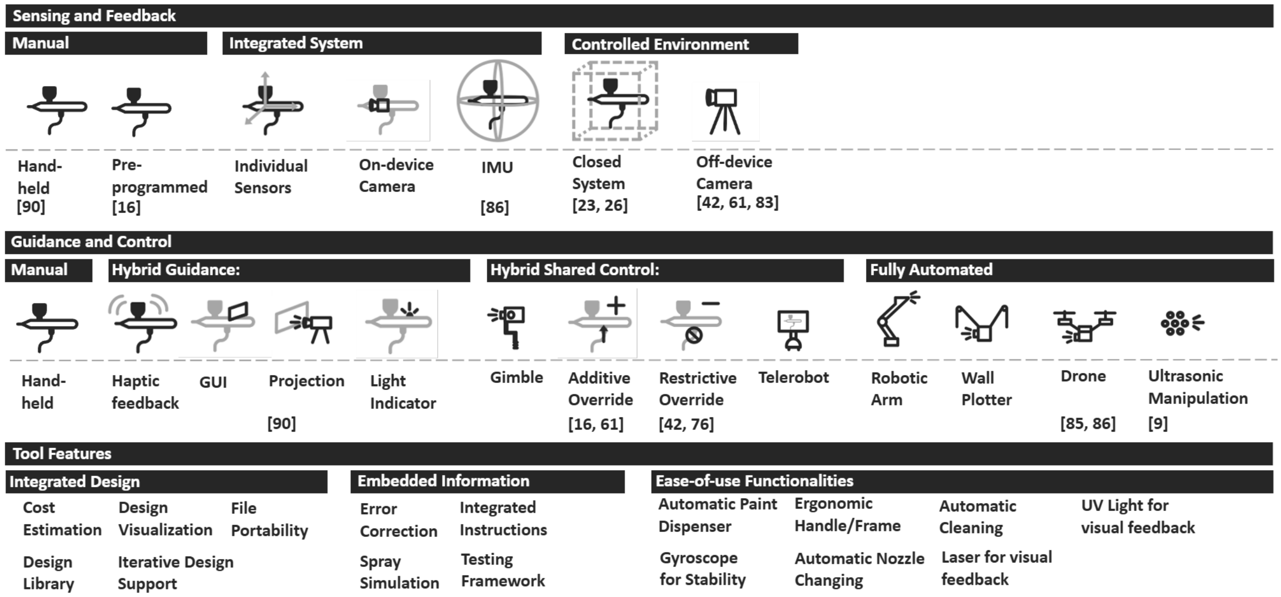

Figure 4: A morphological chart [8] for the feature implementations explored in the context of developing an augmented airbrush tool for spraying EL material. This chart is configured fully as features and modules suggested within the constraints and tool design sections of the design workshops. We include key academic works that have been used to further converge design choices.

[26] and 3D printer [23]) to shape traces. Other work used cameras on or off the spraying device. In a set-up without a camera, [76] uses an IMU to track airbrush position. A reduced design that doesn't track the position of the airbrush and spraying can be carried out without one of these approaches. Sprayable User Interfaces [90] has this system with only system output providing guidance to the user, although this limits the interactivity of fabrication and the support to the maker.

5.1.2 System output: Existing works implement system output ranging from manual maker controlled output, hybrid systems where the user is guided and automated computer-controlled set-ups. Hybrid systems are typically handheld and either guidance or intervention based. Wessely *et al.* [90] use projection to guide the user on a substrate and pre-configured designs, one of the few works exploring spraying of active materials. Elsdon *et al.* [16] implement a single axis custom spray set-up and Prevost *et al.* [61] both override maker autonomy through hybrid approaches. Meanwhile, as both a restrictive and augmentative override systems, Shilkrot and Luk *et al.* [42, 76] both introduce restrictions on spraying to enable automated deposition, while Hooi, Vempati and Uryasheva et al. all explore fully automated means through wall plotters and drones [26, 84, 85].

5.1.3 Tool features: Beyond input and output capabilities of the system we identify a large number of features both from the design workshops that can support fabrication of EL materials (see Figure 4). Since the majority of related works focus around accurate traditional paint deposition (rather than EL specific set-ups), we categorise these features in the context of EL spraying works [23, 90] only. Within the morphological chart, we categorise these features such that they display their inherent modularity to a fabrication system.

5.2 Convergence to Dispray

Based on the morphological chart and design synthesis, we produced several design iterations (Figure 3), ending with the current high-fidelity Dispray prototype presented in the next section. We clarify a set of parameters through which we made choices building off the design choices presented within the morphological chart, and specifically fitting into the need to develop a tool that supported **non-specialist users**, was **handheld** with **high usability**, could **improve adoption** of existing methods and had the **scope to be built upon** in the future. We justify our three core design decisions:

(1) **Hybrid guidance:** We identify the payoff between (a) adopting manual methods that provide accuracy and a range of output than automated systems and (b) automated set-ups that provide reliability and replicability however have greater barriers to familiarity [98]. Dispray implements a hybrid guidance based system due to: (1) complexity of EL deposition (2) From our review of related work, machine spraying accuracy is still sub-optimal.

(2) **An augmented reality user interface:** Following a participant suggestion (P7), we explored the idea of using augmented reality as a platform on which to relay information to the maker in order to reduce the potential for the UI to distract the maker's attention. Most importantly AR also allows for real-time integrated manipulation of virtual stencils and integration of domain knowledge directly into the fabrication environment.
(3) **Usability via compactness and availability of technology:** We identify the benefits of a compact self-contained wireless tool with an onboard camera for portability [66], reduced complexity, avoiding issues relating to occlusion and usability of the system in a single hand to allow for safe manipulation of EL materials. The use of a smart phone provided the platform for an AR user interface, integrated computer vision with inbuilt sensing via an IMU within the Dispray tool while being both affordable and accessible.

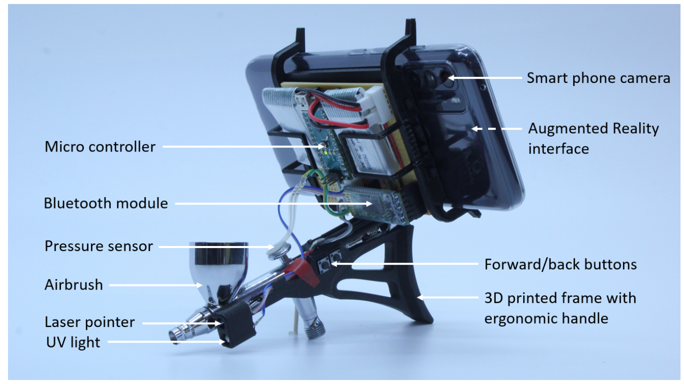

Figure 5: The Dispray tool prototype: an assistive airbrush using AR to guide and teach non- or semi-specialist users in the fabrication of electroluminescent displays.

6 DISPRAY TOOL HIGH-FIDELITY PROTOTYPE

Our Dispray system (Figure 1) is comprised of three core components: a smartphone [50], a 3D printed frame that clips onto an airbrush and a physical circuit with I/O capabilities controlled by an Arduino Nano [3] connected to the smartphone via a bluetooth module [2]. Dispray allows users to place and edit a selected design within AR. It guides the maker through the design steps and fabrication stages through a pipeline that supports novices and makers with more expertise. The tool is wireless, self-contained, lightweight (105g + phone + airbrush) and low cost (total for all parts except the airbrush and smartphone: £41.29 - 2023). To adhere to our design decision (3) of adherence to compactness and availability, we used a budget smartphone (£129 - 2023) with the 3D printed holder allowing for other phone models to be interchanged seemlessly playing off weight and cost. A wireless set-up allowed a minimal impact on the spraying process for which a user must already hold and coordinate multiple items simultaneously.

6.1 System Overview

The smartphone [50] runs the bespoke Dispray App, which runs the AR GUI and controls the whole tool. This decision was made for robustness as well as technological implementation so that makers could use the tool as a prototype. The app is run in Android native using the ARCore library to provide AR functionality [19] and the Sceneform package to handle graphics [71]. ARCore uses the inertial measurement unit (IMU) within the phone as well as computer vision.

The interactive features on the tool handle allow tracking of paint deposition and user actions including a pressure sensor on the airbrush trigger and on-tool buttons that can override the GUI for tangible interaction to support multitasking. The 3D printed frame was designed to be as lightweight and unobtrusive as possible, while being deconstructable for cleaning and transport. Rather than redesign an ergonomic set-up from scratch, we used existing ergonomic handles and iterated on their design (see supplementary materials). The handle is in two parts to help with cleaning which is a necessary step when changing materials.

The app is split into two separate stages which we designate as the "design mode" and the "create mode". The design mode allows for manipulation, visualisation and editing of design incorporating concepts similar to CAD tools and slicers for 3D printing. The create mode acts as a step-by-step fabrication guide centered around a fabrication "Script" (see Supplementary materials). Virtual anchors are placed on the substrate within the virtual AR environment. The system works in a topographically agnostic way, allowing the user to place and manipulate a virtual object as the planned "design" with all measurements being carried out to this object. As a direct result, the system simplifies the processes of surface scanning and precise material deposition allowing for interactive iterative fabrication feedback, while also integrating real-time integrated design processes.

6.2 Design Mode

The maker can place and edit different virtual designs from a design library, allowing a user to visualise where a design will be situated before any material is deposited. Digital templates (Figures 6, 7, 8) open the potential for the design library to be developed into a networked space for makers to share designs. The maker is able to return to this design mode while they are spraying the base electrode, supporting a level of iterative design where tweaks to the object can be made while work is in progress. Three core functionalities are implemented:

Predicting cost: Building on stakeholder suggestions, we implemented a cost function dynamically linked to the scaling of the object. Taking the cost of each material as sold by Lumilor [43, 44] with a tolerance of up to 75% evaporation of material on drying, each cm squared of EL segment costs £0.327 [12]. This is fed back dynamically to the maker as they design their output.

Adding connectors: The user can toggle a design with and without connectors to provide visual support for lateral positioning requirements. These are processes inaccessible to novice users.

Visualisation of layers: We also implemented functionality to visualise the layers that need to be sprayed in AR to give the maker feedback of what would happen in the create mode while still

Figure 6: The design mode of the Dispray system showing: A) the design library where a user can pre-select an electrode layout; B) the uload of the template to AR, shown as a logo that is superimposed onto a physical object, to be used as a virtual template; C) The visualization of layers over a design before any spraying happens.

designing. AR gives us the functionality to provide 3 dimensions to the layers the user could explore.

6.3 Create Mode

This mode is structured around a chronological fabrication pipeline, communicated to the maker through a **script**, building on the concept of instructional workflows [73]. The script has 51 instructions of technical information displayed in the GUI (see Supplementary Materials). This pipeline is split into 5 phases: one for each of the materials deposited. The final phase covers a testing framework. The script was synthesised from information publicly available from Lumilor as the manufacturer of EL materials used [44–46] as well as hobbyist input [34, 35] and our own experience with EL. Core features include an emphasis on PPE and ventilation and technical information such as air pressures at which to spray different viscosities of materials. The create mode encompasses 8 core features, detailed below and each shown in action in Figure 7.

Multiple GUI-based guidance features are supported. **Angle and distance warnings** are displayed to feedback to users based on distance and angle of Dispray to the substrate to support novice users. With shared functionality, a dynamic **depth gauge** is integrated into the GUI to show distance to the substrate providing live data to the user to help guide their spraying. We also integrate a **timer** for drying times, to integrate functionality that would typically be externalised to another device. Dispray further provides guidance support through **out-of-bounds warnings**. This feature helps 1) reduce error of short circuits if different electrodes make contact and 2) compensates for the split of focus between AR and physical space. Such warnings provide guidance and feedback to the user, while leaving control and agency in their hands. To further support split focus between the app and the physical world, we implement **virtual spraying** so that users can see deposition within the AR environment and record their deposition. Using the same functionality we also feedback to makers information regarding **electrode attachment** to build in non-intuitive domain knowledge. Due to the nature of the hybrid guidance integrated in the tool, an isolated experimental assessment of accuracy was deemed as overlapping with related work, where accuracy is determined by the AR "drift" and fidelity of resolution provided by the ARcore package itself [30]. Slocum *et al.* find an average of 1.5cm drift of this tool under significant movement, with Scargill et al. exploring closer variances in drift with the unfocussed move mean of 0.9cm variation being closest to our uses in Dispray [70, 77].

We implement physical add-ons to provide visual feedback to the user. Integrated into the Dispray tool is a program-controlled **laser pointer**. Plumes of sprayed material can be hard to see due to the fine atomisation of material. We also integrate a **UV light.** Beyond difficulty in seeing plumes of material, the EL material is translucent and hard to see. Within tutorials [34, 35, 46], makers are encouraged to use a separate UV lamp to take advantage of the materials photoluminescent properties and assess coverage. Dispray is intended as a learning tool to lower the barriers to entry involved in spraying EL material for novice makers. As such, we implemented different skill levels embedded within the app. A maker can indicate their skill level (novice, intermediate, advanced) to gradient information including bespoke fabrication tips, and tool features such as the positional warnings and active tool guidance features. Beyond these features, 8 modular functionalities are enabled within Dispray.

We also developed an easy-to-follow testing framework to help users identify common issues, determine whether they are fixable, and understand how to address them (see supplementary materials). This was motivated by a gap in the literature on effective troubleshooting of EL devices, likely due to the early stage of the field. Even in existing material documentation, makers are often simply advised to contact the manufacturer. We also include the Dispray App APK and circuitry within the supplementary materials for replicability, evidence of feasibility and further development.

6.4 Demonstration of Functionality

Figures 1 and 8 show four applications created by the authors, using over six years of experience with the materials, fully produced with the Dispray prototype and all its built features presented above. Specifically, the base electrode was placed using the design within AR. No masks were used within this process, although as suggested within the pipeline, a flat handheld hard edge/french curve was used to prevent short circuits on base electrodes, by covering exposed copper paint when applying the transparent conductive electrode layer.

We created an addressable mixed gender toilet sign, an interactive label on a bottle, a door bell icon on a penholder and an indicator on a bike helmet. These demonstrations represent the ability of the Dispray tool to support "free-hand" layering of electrodes to create interactive surfaces. These examples of displays draw from related work, in particular [20, 23, 31, 55, 90].

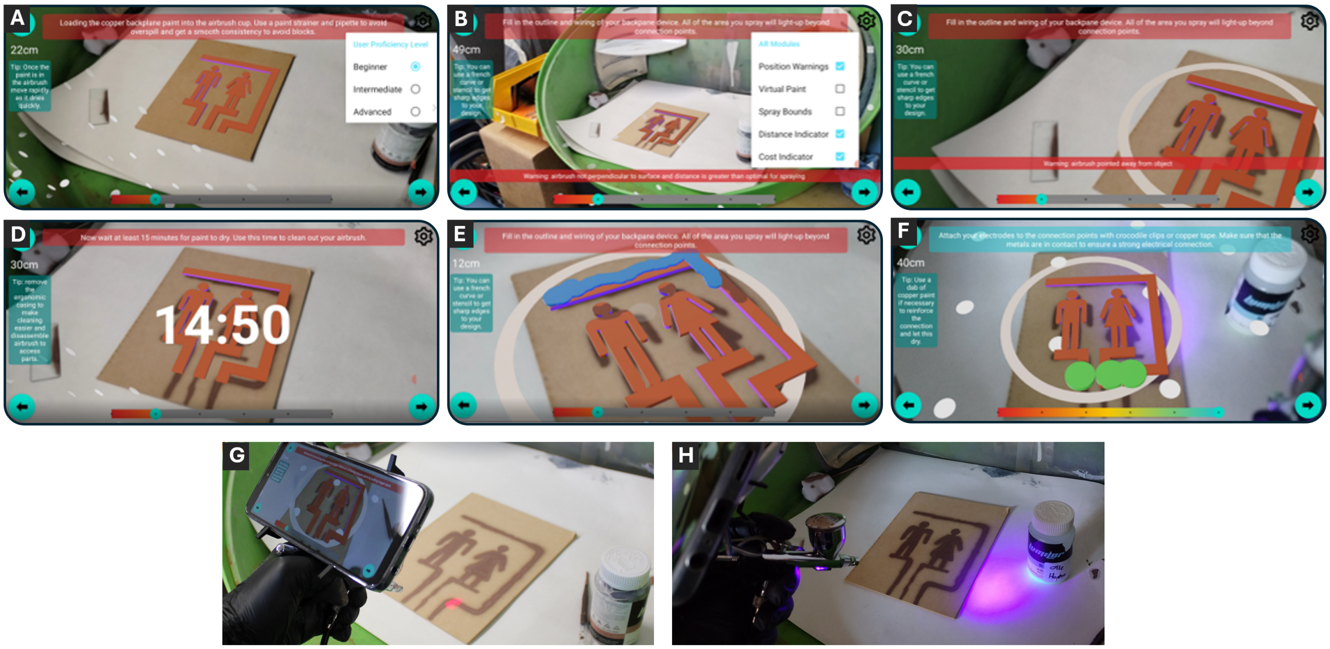

Figure 7: A walk-through of the Dispray tool UI and functional tool features. Full text prompts are outlined in Dispray script in Supplementary Materials: (A) the process is outlined and conveyed through 51 instructions. Additional tips and information can be toggled by users. (B) Warnings for the angle from perpendicular and distance from plane of the airbrush (C) Out-of-Bounds warning showing when the spray is not directed at an electrode. (D) Integrated timer to aid appropriate drying times. (E) Virtual spraying shown in blue within the AR set up to provide feedback on deposition. (F) Integrated electrode attachment information and testing framework. (G) Laser pointer on trigger press to aid deposition, as well as virtual overlay (blue). (H) Digitally controlled, integrated UV light to show EL phosphor.

7 STUDY 2: STAKEHOLDER EVALUATION

We carried out in-person interviews and walk-throughs of the high-fidelity Dispray prototype with the stakeholders from Study 1. This enables us to not only get feedback on the usability of the tool through those with expertise in art and engineering, but also to get feedback on the design and development processes themselves. Study 2 aims to "close the loop" by consulting the same participants as Study 1, providing information on the functionality and efficacy of design of the Dispray tool with the perspectives of the original design workshop. By gathering this feedback we evaluate how well the design parameters in Study 1 can be combined and by extension a validation of the insights generated for RQ1. In addition Study 2 draws on participants independent expertise, specifically opting for 1:1 engagement to understand participant perspective more deeply. This enables insights into how Dispray can support adoption of EL technologies within the context of both artistic practice and as an engineering tool. We argue that re-engagement with engineers and artists en-lieu of specialists provides the grounds for valuable insights, in the context of RQ3's focus on adoption, as there is not yet a significant user base of people who spray active materials.

Study 2 and Study 3 simultaneously provide evaluative measures for the Dispray tool and each explore both RQ2 and RQ3 on the efficacy of the Dispray tool and the scope for adoption from perspectives of the stakeholders and novice non-specialist users.

7.1 Experimental Set-up

We carried out semi-structured 1-to-1 interviews with the original speculative stakeholders, including the opportunity for participants to hold, run-through and explore the Dispray tool. P4 dropped out, resulting in 6 women and 5 men. The studies were carried out in person. We started with a 10-20 minute walk-through where participants held and experimented with the tool. Participants were provided with a summary sheet of key features of the Dispray tool in order to remind them as they went through, as well as a cross-sectional diagram of the physical tool features (Figure 5). The interviews lasted between 30 and 90 minutes. A full run through of the app was demonstrated with participants then having a run through of the tool. Participants did not create an artifact for safety and practical reasons as the interviews were held in their home environments to enable engagement with a greater range of specialisms for the whole study. We recorded the conversations as audio files. Discussion was prompted regarding the feel and the functionality of Dispray. We found 5 core themes of reflection from stakeholders.

7.2 Theme 1: Appreciating the Design While Navigating Trade-offs

The core system design choices received largely positive feedback from participants. P6 and P3 noted it had *"exceeded expectations"*,

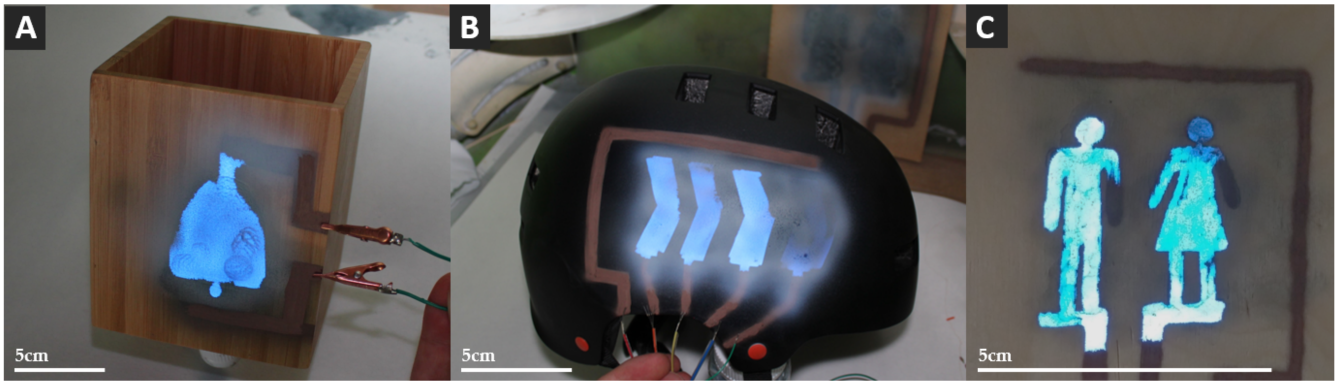

Figure 8: As experts in spraying EL, we (the authors) produced demonstrations using the Dispray tool high-fidelity prototype to demonstrate core functionality of the tool. Shown here are a (A) doorbell notifier, (B) an interactive cycle-helmet indicator and (C) an adaptive toilet sign.

while P6 and P7 highlighted its compactness and accessibility. P7 supported the overall balance of features stating *"it doesn't feel like a sort of Frankenstein monster of features"*. Meanwhile P11, critiques the linearity of the pipeline for use beyond novices stating *"being stuck in this kind of flow will be restrictive"*. Regarding the hybrid output, participants were divided on the balance between manual control and computational input. P1 and P7 favored the guidance system, while P9 and P2 saw value in incorporating some computational control. Smartphone use was praised for familiarity, but its weight was a common complaint, with P11 suggesting, *"it's going to be heavy like a drill"*, and others recommending counterweights or wrist support (P7, P10). While AR was seen as promising (P3), it faced challenges like surface detection and object drift (P11). Finally, participants raised issues around the tool's robustness and ergonomics, suggesting improvements to the handle's design and material quality (P11, P10). Overall, feedback emphasized the need for refinements while recognizing the tool's potential.

7.3 Theme 2: Valuing Structured Support and Envisioning Future Possibilities

Participants were largely positive about the implementation of modules and features in Dispray. P6 highlighted that the step-by-step guides were their *"favourite part"*, and P10 noted that *"the level of interaction... would be very helpful with working out something you might not be able to work out yourself"*. P2 and P9 appreciated the breakdown into phases, with P7 emphasizing the importance of having the information *"all in one place"* and *"from a trusted perspective"*. This feedback shows the value of integrating material-specific domain knowledge within a tool. Regarding the graphical user interface (GUI), P7, P11, and P2 suggested improvements, such as P7 recommending a *"tidy up"* of the interface and P9's suggestion to redesign it like existing illustration software. However, P6 found the GUI to be *"really user-friendly"*, and P11 noted that the tool and supporting information had an *"actually really good UI"*, due to its clarity.

Participants were positive about the design and create modes, with P9 affirming that the modules *"all have a reason for being there"*, while P5 and P11 praised Dispray's compactness, eliminating the need for separate tools. P12 suggested improving the angle warning with granular feedback. Meanwhile, P9 emphasized its potential as a teaching tool. Several new module ideas were suggested, including 3D printing for stencil creation (P12) and the projection of domain information onto the substrate (P3), who envisioned *"a physical manifestation of a virtual object using projection"*. P3 also proposed electro-muscle stimulation to *"stimulate them to actually be more accurate"* [40, 41]. These ideas, along with practical suggestions like voice prompts (P10), guide future developments to enhance the user experience.

7.4 Theme 3: Supporting Novice Learning While Navigating Expert Limitations

This theme explores how participants viewed Dispray as a learning and support tool for the deposition of EL displays, particularly in fostering confidence and guiding novice or semi-specialist users. Discussion focused around the feature of the "Skill level modifier", with an overall positive impression on Dispray's potential as a teaching tool. For example, *"I think [it's] generally, very, very useful for that entry level user, sort of taking people to that intermediate"* (P7). P5 and P9 focused on the ability of the tool to build confidence *"then I can build my confidence and how to how to do it [using this tool]"*. Participants also discussed the type of learning fostered by the tool. P12 highlighted that *"this is an educational tool because it's one informing you about the process"*. P2, P11 and P5 each reinforced the educational factors of domain knowledge but rather than teaching it from scratch suggested the benefits related to reminders. This promotes the strengths of Dispray as an ongoing learning and support tool for novice users.

Dispray's non-specialist target audience was clear for P1: *"Definitely for nonspecialists... it would make a really good training wheels"*. Participants raised concerns with the transferability of function to skilled makers. P5 thought the tool would still have value: *"the advanced [users]… we just easily get caught… It makes the whole process go really smooth"*, however P7, P2 and P1 provided more skeptical perspectives on how useful the tool is for specialists, for example stating *"If you've got people that have already got experience, I think it becomes a different tool"*. For the warnings, P1 stated that *"I think if I was an expert that would get annoying"*. Participants suggested alternative related user groups for tool adoption, such as artists (P8, P12), technicians (P8), training industrial staff (P5), fabrication hobbyists (P8, P12) and students (P9, P5). They also re-emphasised the key theme of prohibitive expense ingrained in the tool design (P12, P8). Discussions suggested that the use of the tool is indeed appropriate for semi-specialist users.

7.5 Theme 4: Separating Creation from Use: Visions for Deploying Dispray

P7 and P8 envisioned decentralising production, P12 proposed independent creation through 3D printing and P8 suggested, *"there could be a technician who does this. And it's a service that somebody can go in for a small object and take it and they do that better"* allowing others to utilise the tool without needing to build it themselves. P7 supported this, highlighting the *"power of additive manufacturing"*, where *"some people want to create, but not spray,"* emphasising the separation of design and fabrication roles, similar to current 3D printing trends.

Participants saw potential for using Dispray's technology in other fields. P6 suggested that incorporating a smartphone into tools has *"a really wide breadth of potential reach within manufacturing"*, while P1 and P12 proposed adapting Dispray for traditional painting and artwork. Suggestions for future work included expanding community engagement. P7 proposed *"community-built guides"* while P10 and P12 suggested integrating support features, such as a help button linking to resources. With its smartphone integration, Dispray is well-positioned for these community-driven developments.

7.6 Theme 5: Reflections on the Design Process: Valuing Inclusion and Iteration

Participants were positive on the design process, stating *"it was guided, I thought that got the best out of everyone"* (P6) or *"the process has been good"* (P12). P9 in particular was positive about both the outcome and the process of being involved stating *"I like how you can give feedback at different stages"*. P7 commended the fidelity of the convergence of design ideas stating "It's very, very close to a lot of the ideas that people had". P3 and P12 each discussed the *"fine balance between like, what, between how much to consult people? And how much just to go with your own ideas?"* (P3). Notably, participants took ownership over the designs and the tool that was produced.

7.7 Summary

Through interviews with stakeholders, we gathered feedback on the Dispray system, evaluating its usability, design choices, and broader functionality. Participants praised the tool's cohesive design, noting it was neither *Frankenstein-like* nor *overly complex*. Positive feedback highlighted the tool's compactness and potential for adoption, with P6 and P3 noting it had *"exceeded expectations"*. While stakeholders appreciated the overall design, there were suggestions for improvements, such as refining the graphical user interface (P7, P11) and addressing issues with weight and camera positioning (P11). The potential for Dispray as a learning tool was affirmed, with comments on its effectiveness in teaching and building confidence (P7, P5). Overall, the feedback was positive, emphasizing Dispray's promise while also identifying areas for refinement and expansion.

8 STUDY 3: EVALUATION WITH NOVICES

We ran a follow-up study to examine how novices used Dispray. Participants had no experience with airbrushing, engineering, or EL materials. The goal was to see how well Dispray supports beginners in fabricating EL displays through continuous real time guidance. Across several sessions, they worked with the tool while we observed and interviewed them to understand how it supported their learning of EL spraying.

8.1 Experimental Set-up

The 4 novice participants (P13-P16) each carried out 3 distinct sessions. Each session involved a 60 minute spraying session and a semi-structured follow-up interview. In the first two sessions the interviews lasted 45 minutes and on the last day they lasted 30 minutes. The Dispray tool was presented to the participants in three forms. The full integrated functional tool, just the mobile phone and Dispray app and a printout of the Dispray walk-through script. Participants were also provided with the active materials used in EL display fabrication [43], as well as a piece of card which they were specifically only instructed to use for covering base electrodes to prevent short circuits. Participants were instructed to explore the Dispray tool and given the goal to construct an EL display. They were encouraged to split their time over multiple sessions where necessary, and in all cases due to mistakes and accommodating for drying times final outputs took at least 2 sessions resulting in 4 working prototypes (see Figure 9) and a number of partially complete designs (see Supplementary Materials). The participants were pointed towards the virtual designs in the app, but were given creative freedom to use the tool and materials in whatever way they saw fit.

The authors provided safety guidance when asked for but redirected participants to the Dispray tool for specific domain knowledge-related questions. We encouraged speak-aloud procedures from participants and took observations of their handling of the tool. Interviews explored the learnability of the process, functionality and familiarity with the Dispray tool, comfort levels with EL spraying and potential for adoption.

Due to the use of paints including toluene, spraying was done in a "Lab Bubble" [36], on desk open ventilation, with full ethics and risk assessment complying with our institution's standards. Participants were provided with appropriate PPE (nitrile gloves and respirator). The study set-up is shown in Figure 1 (D). The airbrush itself was cleaned between materials by the author so as to preserve its functionality. As observers, we primarily focused on Dispray's capability to support creativity and the learning process, as well as issues that arose with using the tool. We found that 4 core themes emerged.

8.2 Theme 1: Weighing up of Information Presentation: Script vs App vs Tool

Participants were presented with the Dispray tool in 3 forms: Script, app and full tool. Discussion from participants highlighted the importance of supporting information in guiding their efforts in fabricating displays with a reflection on whether information presented in one go or continuously was more important, and the role that the full tool played in the guidance of their spraying process. They discussed the balance between receiving information all at once or continuously. P15 stated *"I find [the script] the easiest"* whereas P14 had a preference to *"Integrate [domain knowledge] more continuously, within the spraying process"*, rather than the app. P14 expanded that the app helped manage the quantity of information vs the script. P16 noted that understanding carcinogenic risks made it preferable to *"read through the manual before"* starting, emphasising that having a clear overview in advance of spraying was important. P15 expressed that *"I'd rather a step-by-step than a briefing."*, further emphasising the ease of use from a step-by-step supporting guide. P13's perspective aligned with P15, stating *"I think its a good idea for instructions on the screen to avoid having to look at the script"*. Split perspectives on the method of integrating domain knowledge supports implementation of a tool that gives this agency to the user when guiding their fabrication process. Overall, the script's core information was well received while the medium of delivery proved divisive.

8.3 Theme 2: Effectiveness of Prototype and Ergonomic Constraints

Participants offered mixed feedback on the prototype's usability. P14 observed that *"how it sprays, the distance and precision... improved but it's still not perfect."* P15 mentioned that the prototype was *"not suitable for all surfaces"* and became awkward to use over time. Both highlighted the need for a more compact and user-friendly design, with P14 noting that *"a cleaner and better-balanced prototype can help"* and P15 stating *"after a while, it starts getting uncomfortable with the way you hold it"*. P16 reflected on the strengths of the GUI design choices, stating *"obviously AR is a good tool... for presenting real time prompts"*. Over multiple sessions, we observed that participants relied heavily on the script (see Supplementary Materials) itself and that the primary focus of the tool emerged as a way to deploy the instructions effortlessly. We distinguish ergonomic use of the tool relative to its general usability. As in Study 2, participants pointed out challenges with bulk and handling. P16 mentioned a misalignment between where the object appeared on-screen and its actual sprayed location. This reflected performance issues, especially with the tool's interface and precision. On the other hand, P15 observed how the tool was *"manageable"* after a day of use, but this would become an issue with repeated use. Overall, participants emphasised the need for ergonomic improvements and more refined design features to enhance usability, however key features of Dispray including the fundamental presentation of information on a tool mounted AR set-up were highlighted as supporting their workflows as novices.

8.4 Theme 3: Supporting of Learning and Reflections on EL Complexity

Dispray was described as intuitive to use after several sessions. P15 found it *"pretty easy to use"* by their third session, and P13 remarked in their second session that the app became more intuitive with time: *"The app is easier to navigate today, maybe I got used to it more than I thought"*. However, P14 expressed concern about the difficulty of navigating the prototype in isolation. P15 and P16 differed in their opinions on whether in-depth information and terminology was necessary. P15 stated *"I just want to know what I can do but I don't care about the [scientific] terms"* and a request for more *"intuitive image instructions"*, while P16 expressed an interest in understanding more about the *"fundamentals of spraying these materials"*. We observed that the tool became more intuitive with use, and participants had differing preferences for the granularity of technical detail provided.

Participants found the EL spraying process accessible, with an increasing familiarity over time. P13 stated that *"Learning was OK. As we worked on it three times, it kept on getting better, but challenges, like the troubleshooting... are still complicated"*. P14 analogised that the *"Process is simple, is kind of like cooking"*. P13 mentioned that without the script or tool, there was *"no chance"* of understanding the process intuitively, emphasising its complexity but also the key role of Dispray as a tool for engaging novice learners. P16 reflected that as a whole airbrushing was *"quite easy to use"* but that EL spraying was *"more complicated with different chemicals... high threshold"*. While participants grew more comfortable with the process, the complexity and technical demands of EL spraying remained evident.

Participants appreciated the guided learning but found the device challenging to use independently. P13 stated *"The learning process is easy with instructions provided. Without instruction, I think I might struggle to grab information and use the prototype by myself"*. We observed frequent referral back to the app and script during the learning process, however we speculate that the use of an integrated tool such as Dispray may detract from natural exploration and the process of learning through making.

8.5 Theme 4: Reflections on Adoption of Presented Technologies

Participants saw potential for the tool in creative industries and hobbyist markets, drawing comparisons to 3D printers. P13 remarked that *"I think it could have a similar trajectory as 3D printing... hobbyists might pick it up, but the complexity might hinder the process"*. Participants acknowledged that the tool's complexity could limit broader adoption unless the setup is simplified, and the learning curve shortened. P14 stated *"If I were an artist or doing some artwork, then it would be useful. But the process and the chemicals make me a*

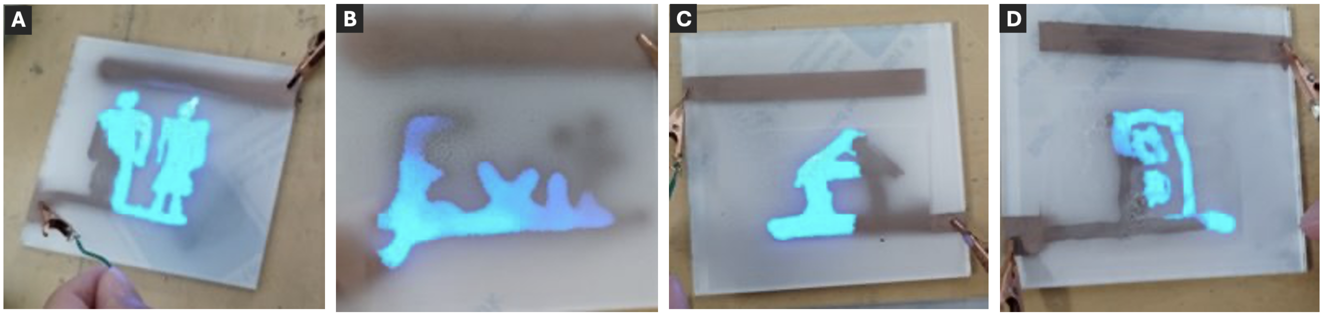

Figure 9: EL display types produced with the Dispray prototype by non-specialist novice users. Due to the hand-held nature of the Dispray tool, note the lack of high end edge resolution, masking was only implemented via a piece of card for the base electrodes, the bars at the top of the images, to prevent short circuits. As a result of limitations relating to experience, note the partial functionality of each segment, indicating inconsistent layer thicknesses.

bit hesitant.", while, P15 also proposed *"Maybe [I would use the technology] as a recreational thing... it's interesting, but I don't see myself using it daily. It could be a good hobby for weekends."* P15 presented concerns about health and safety, while P16 was concerned about use around *"kids or older people"*. Participants engaged with suggesting improvements to the Dispray tool, including automation. P16 proposed *"smoothening"* the layers of paint through automated deposition, while P14 suggested that the process would be *"much easier with a video"* integrated into the tool. Despite recruitment of participants specifically without interest in this technology, the integration of participants within the process appears to have drawn participants to potential future engagement with the process.

8.6 Errors from Participant Spraying

Further to participant feedback, we observed three different types of errors in participants spraying EL materials. These are characterised in three different forms: A) over- and under-spray of active materials; B) poor airbrush positioning and spray intensity and C) misordering of layers. We highlight how these errors have led to partial or full failure rates. By over- and under-spraying (A), we refer to participants spraying beyond intended borders or patterns or not spraying up to intended boundaries. We observed that overspray was far more often the case resulting in **poor boundary accuracy** (such as in Figure 9B). We carried out a cursory analysis, overlaying the design forms onto the easily observable copper traces on samples that novice users sprayed and found that this inaccuracy spanned from 10% to 35% beyond intended boundaries. Showing underspray, all 4 of the examples in Figure fig:Participantoutputs show EL **patterns that do not fully illuminate** with likely the EL-phosphor not being sprayed. Figure fig:Participantoutputs shows two failures as a result of overspray (10A, 10B) where overspraying conductive material has connected top and bottom electrodes causing a **short circuit**. This is straightforwards to verify with a multimeter. Airbrush positioning and spray intensity (B) was only problematic when spraying material with too high a velocity or as a result of being too close to the substrate, where less deposition could easily be rectified by another pass with the airbrush. This is illustrated in failures of Figure 10D, and in particular through spraying of PEDOT:PSS. Here we can see that too high-intensity has caused beading of the active material resulting in **inconsistent coverage** and therefore non-conductive electrical properties. Lastly (C), due to mistakes on ordering layers, devices **failed due to layer misorder**. This was caught twice in the novice study and in both cases the samples were discarded without being finished so as to enable participants to fully engage with the tool.

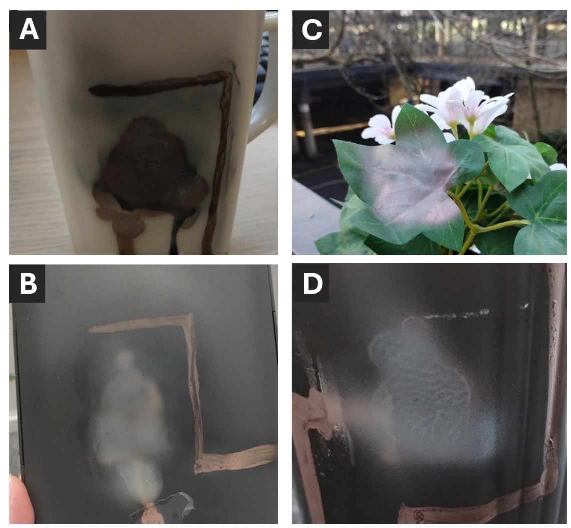

Figure 10: EL Displays with faults produced by participants of a novice study over the course of 3 days such that they do not light up. Shown: A and B have a short circuit; C has inconsistencies across both electrodes due to the porous substrate; and D, has inconsistent conductivity on its top electrode. All failures are serious enough to not show any luminescence.

8.7 Summary

Overall, participants with no prior related specialisms were able to engage with complex domain knowledge through Dispray and learn a state-of-the-art personal fabrication process integrating active materials (Figure 9). The insights from the novice learning study evaluation provided a new perspective, revealing both the strengths and weaknesses of the Dispray tool. Specifically we conclude that Dispray supported learning as well as functional fabrication.

9 DISCUSSION

We set out to answer several key questions related to the design and evaluation of Dispray as an augmented airbrush supporting non-specialists in handling active materials. We conducted three evaluations as well as a demonstration of Dispray's functionality through sample applications. The insights from all three studies provide a broad set of insights spanning the three research questions. In this section, we synthesise these results to provide answers to the three proposed research questions.

9.1 What are the Design Parameters for a Tool to Support Active Material Fabrication?

Evaluative feedback from stakeholders indicated that the Dispray tool aligned well with their expectations, both in functionality and in its reflection of an effective design process. While the core of the tool represents integrated domain knowledge, the medium of conveyance to the user and supporting features have significant divergence of design option.

The strength of the Dispray tool lies in its deviation from the author's initial design assumptions, as a result of engagement with engineers and artists. Early ideas revolved around either a handheld airbrush tool or an automated spraying rig. In this case, through collaborative workshops, new features including augmented reality, smartphone integration, and varied structural designs were incorporated. These additions enhanced the final product, demonstrating the value of iterative design and participant input. The positive feedback in user evaluations reinforces the strength of this approach. We argue that the strength of the Dispray tool itself, both in functionality and as a learning tool, reflects the benefits of the design process of engaging stakeholders.

Discussions and emergent themes represent generalisable design parameters for various deposition methods and active materials beyond spraying EL. Specifically, while the design parameterisation of hybrid guidance, AR as an interface and an emphasis on compactness (subsection 5.2) allowed us to attain the goals of functionality and support as a learning tool within contemporary technological constraints, further work should consider alternative parameterisations. For example, revisiting parts of the morphological chart such as hybrid guidance, if design tools can be suitably extended to compensate for the limitations of computer-aided design environments, then the emphasis on hybrid guidance could be revised to a fully automated option. We propose addressing these questions of full automation [76, 85] with active materials and exploring how a maker can intercede with design while fabrication is in progress to both respond to expert evaluation and mitigate issues raised by novices. We propose drawing in concepts including interactive fabrication, inspired by works such as RoMa by Peng *et al.* [59].

We treat EL deposition as a use case for a broader range of active materials [21, 38], in particularly we identify that many active materials can be deposited additively through methods such as spraying [28, 89, 95, 97] and as such argue that our broader aim in Dispray of improving adoption can be translated to other active materials. In particular we highlight that the design parameters surfaced through Dispray: hybrid guidance, embedded domain knowledge, and real-time AR support, generalise beyond EL spraying to other active-material processes. These results reinforce Baudisch and Mueller's framing [4], that reducing cognitive load and foregrounding learnability are not peripheral concerns but central mechanisms for enabling non-specialists to meaningfully participate in material-centric making. The lessons we observe, particularly the role of active, situated support and gradual transfer of expertise, offer a transferable blueprint for active material tool design.

9.2 How Effective is Dispray?

Dispray as a tool for learning: Drawing information from studies 2 and 3, while Dispray found clear use as a tool to support learning, various limitations also emerged. Novice users expressed increasing comfort with the Dispray tool as they gained experience, with participants such as P15 stating it became *"pretty easy to use"* by their third session. This reflects the tool's ability to scaffold learning over time, gradually allowing users to feel more confident with both the process and the technology. Specialist stakeholders also responded positively, acknowledging the Dispray tool's potential as a learning device, especially in making complex processes more accessible to those with limited technical backgrounds. However, limitations emerged regarding the physical tool's ability to convey information compared to the more structured script. The way information is presented, all at once or incrementally, is crucial in a complex fabrication process. These diverse learning preferences reflect broader patterns in how people engage with new skills, highlighting the need for a flexible approach to information delivery, particularly important with novel material-centric processes due to their inherent complexities. While the Dispray tool offers an entry point for learning, ongoing support after the initial uses would be essential to sustaining user engagement. Highlighted from interviews with original participants is the requirement that to support continued learning such a tool affords opportunities to integrate community support, potentially creating networks of users who can share tips, experiences, and innovations.

Dispray as a functional support tool: The base level functionality of the Dispray tool is demonstrated through the expert-made demos (Section 7) and the feedback from the novice participants (Section 8). Figures 1, 8 and 9 accurately show that the tool itself is functional. We note incomplete luminescence and low resolution as symptoms of skill thresholds and the design of a completely hand-guided tool. We contextualize these in our own experience of spraying EL, and the core technology holding high failure rates. Participant errors resulted in more than 50% of produced displays failing, however as the novice user study was carried out we observed diminishing failure rates with successful displays being largely completed on the third day of the study. The Dispray tool offers several unique features that set it apart from other augmented spray tools: 1) In-built domain knowledge for EL active materials, 2) integrated design features allowing for iterative digital manipulation of designs, 3) an augmented reality interface and fully self-enclosed systems to support compactness.

Ergonomics of Dispray: Participant feedback highlighted effective and ineffective parts of the tool in both Studies 2 and 3. With high priority, from both evaluative steps, was the limitation in the ergonomics of the tool due to weight and where the mounted phone moves the center of gravity. We also note consistent issues with bugs in the system, largely centered around the bluetooth module's reliability. Beyond these, the implementation of AR (suggested by P7 in the design workshops) was positively accepted by participants as an interface choice to span complex domain knowledge and application within the fabrication process. A repeated theme was on stenciling and accuracy through stakeholder interviews and novice run-throughs. We return to the core issue of whether the device should automate deposition. This was dismissed within our convergence of designs due to current technological limitations, evidenced through related work on assistive airbrushes [16, 42, 61], but with recent explorations into in-air manipulation of deposited active particles [9] we aspire to further explore this in future work. We reflect on our design parameterization here, as the self-contained and compactness thresholds are clearly linked to ergonomic limitations. The self-contained nature of the tool allowed for easy deployment, autonomy of users with regards to how much they engaged with the physical prototype and both low-cost and low overheads for setting the tool up. Concerns regarding ergonomics suggest several future directives. We aim to iterate on the Dispray design with a lighter-weight tool design in the future. One of the core design concepts founded in related work was the self-contained nature of the Dispray tool initiating the implementation of the phone-mounted AR, however user evaluation has led us to explore head-mounted alternatives for further design steps.

9.3 How Does Dispray Support the Adoption of Core EL Technology?

Participants provided positive feedback on the potential adoption of the Dispray tool, particularly within creative industries and among hobbyists. P13 suggested it could follow a similar trajectory to 3D printing, where complexity may limit its use by casual users, but hobbyists could embrace it. However, some raised concerns about the prohibitive costs, health and safety considerations, and the complex entry barriers beyond domain knowledge and skill level. These factors could limit broader adoption until further improvements make the technology more accessible. Novices and expert evaluators demonstrated comparable understanding of the conceptual ideas around EL structures. Contrary to our expectation, the novice users were quick to understand the EL layer structures with minor concerns complexity (P13). The participant who could be categorised as struggling with concepts around EL deposition was the artist P9.

We further note that in follow up work two of the twelve original stakeholders have further engaged in work with EL technology, one in a research capacity and the other in a commercial context (beyond P5 who had already worked with EL technology). Although we can't draw generalisable results from this small a sample, this study indicates the benefits to adoption through engaging stakeholders within fabrication tool design. In summary, while the Dispray tool offers a promising starting point for both novices and specialists, its long-term success will depend on refining usability, reducing costs, and providing ongoing support to foster a broader community of users. Within the maker movement and conventional 3D printing, not only is personal fabrication a tool to rapid prototyping [4, 53] and decentralised production [25], but it is also a platform for decentralised development of technology beyond industry and academia. We propose that this promise of adoption and increased engagement suggests a compounding effect. The development of tools for non-specialist use of active materials not only supports non-specialists in the short term, but also empowers them to make further developments. We propose this as an avenue for promising future work.

9.4 Limitations and Future Work

Both the design workshops and the evaluations were founded on qualitative methods. In order to appropriately address our research questions, we determined that we needed to explore both the lived perspective and skill sets of both makers (Study 2) and novices (Study 3). In particular, given Dispray's goals of guiding process and supporting learning for non-specialists areas, in Study 3 we opted to engage with few participants deeply and identified that quantitative metrics alone would lack sufficient depth to allow us to explore a tool that can support a range of maker perspectives. We encourage future research to complement this with quantitative studies that measure specific benefits of Dispray and similar digitally augmented fabrication tools.

The participant numbers in all studies reflect the highly specialized maker community involved in the workshops. Engaging experts with deep domain knowledge was essential to gain detailed insights into both the technical and creative constraints of Dispray. In Study 3, we prioritized longer, repeated sessions with fewer participants to collect rich, in-depth experiences rather than broader but shallower feedback. Nonetheless, we acknowledge that these specialized perspectives may limit the generalizability of our findings. Study 2 and 3 were deployed together on the same iteration so as to allow us to accurate answer RQ2 and RQ3. In our future work we plan to further iterate on the Dispray prototype and its design and to engage with a broader range of non-specialist stakeholders. While the current Dispray tool prioritizes supporting creativity over fine resolution, we propose this as the most important intersection to address moving forwards.

While the design workshops themselves provided a rich space to inform the Dispray tool design, we acknowledge that the limited format of design workshops [65] and subjectivity of a single final high-fidelity prototype mean that this acts as only one of many possible solutions. Our core direction for future work include the promise of material-centric methods [21], specifically automation. Following the rise of conventional 3D printing, full automation promises replicability of results, scalability, precision and use of integrated design. However, the study presented here indicates strengths to integrating learning processes, understandings of materiality and continuous creative input. We propose that the next iteration of Dispray has the scope to take on interactive fabrication [59, 92] to enable continuous design and extend the insights on the learning process with automated parts of the process.

We also suggest researching the long-term development and support of maker communities around active materials. Our findings show enthusiasm for these practices, even among novices, but ongoing engagement was beyond this study. Integrating with existing communities or creating new networks could harness the cross-pollination of ideas and excitement observed.

10 CONCLUSION

We explore the design and development of an augmented airbrush to engage with the challenge of non-specialist adoption of active material personal fabrication. In developing the Dispray tool through engagement with artists and engineers, we draw inspiration and direction from a range of perspectives which are then synthesised into a high-fidelity prototype of a tool. Dispray supports both the functional process of non-specialist manipulation of materials but also the learning process involved. This is demonstrated through engagement with initial participants and use by novice users. Active material fabrication is the key to unlocking free-form interaction as well as holding the potential for automation. This work presents a range of insights necessary in the step towards fully supporting non-specialist use of active material fabrication methods.

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REFERENCES

[1] Harshit Agrawal, Udayan Umapathi, Robert Kovacs, Johannes Frohnhofen, Hsiang-Ting Chen, Stefanie Mueller, and Patrick Baudisch. 2015. Protopiper: Physically Sketching Room-Sized Objects at Actual Scale. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 427–436. https://doi.org/10.1145/2807442.2807505

[2] Arduino. 2022. Arduino Bluetooth module: https://electropeak.com/hc-05-bluetooth-module. Last accessed August 2022.

[3] Arduino. 2022. Arduino Nano: https://store.arduino.cc/products/arduino-nano. Last accessed August 2022.

[4] Patrick Baudisch, Stefanie Mueller, et al. 2017. Personal fabrication. *Foundations and Trends® in Human–Computer Interaction* 10, 3–4 (2017), 165–293. https://doi.org/10.1561/1100000055

[5] Anna Dagmar Bille Milthers and Markus Lochtefeld. 2021. ChromaBot - Prototyping Soft Robotic Actuators with Integrated Electrochromic Displays. In *20th International Conference on Mobile and Ubiquitous Multimedia* (Leuven, Belgium) *(MUM 2021)*. Association for Computing Machinery, New York, NY, USA, 198–200. https://doi.org/10.1145/3490632.3497831

[6] Sam Bourgault and Jennifer Jacobs. 2024. Millipath: Bridging Materialist Theory and System Development for Surface Texture Fabrication. In *Proceedings of the 2024 ACM Designing Interactive Systems Conference*. Association for Computing Machinery, New York, NY, USA, 50–68. https://doi.org/10.1145/3643834.3661599

[7] Jesse Burstyn, Nicholas Fellion, Paul Strohmeier, and Roel Vertegaal. 2015. Printput: Resistive and capacitive input widgets for interactive 3D prints. In *Human-Computer Interaction–INTERACT 2015: 15th IFIP TC 13 International Conference, Bamberg, Germany, September 14-18, 2015, Proceedings, Part I 15*. Springer, Sprinter, London, UK, 332–339.

[8] Stuart K Card, Jock D Mackinlay, and George G Robertson. 1991. A morphological analysis of the design space of input devices. *ACM Transactions on Information Systems (TOIS)* 9, 2 (1991), 99–122.

[9] Oliver Child, Ollie Hanton, Colin Kellett, Matt Sutton, Bruce Drinkwater, and Mike Fraser. 2024. Tangible Explorations of Sonolithography. In *Proceedings of the Eighteenth International Conference on Tangible, Embedded, and Embodied Interaction*. Association for Computing Machinery, New York, NY, USA, 1–14.

[10] Victoria Clarke and Virginia Braun. 2017. Thematic analysis. *The journal of positive psychology* 12, 3 (2017), 297–298.

[11] Bare Conductive. 2020. Bare Conductive Paint: https://www.bareconductive.com/shop/electric-paint-50ml/. Last accessed April 2020.

[12] Demonpaint. 2022. DemonPaint: https://demon-paint.com/. Last accessed September 2022.

[13] Laura Devendorf, Leah Buechley, Noura Howell, Jennifer Jacobs, Cindy Hsin-Liu Kao, Martin Murer, Daniela Rosner, Nica Ross, Robert Soden, Jared Tso, et al. 2023. Towards mutual benefit: Reflecting on artist residencies as a method for collaboration in DIS. In *Companion Publication of the 2023 ACM Designing Interactive Systems Conference*. Association for Computing Machinery, New York, NY, USA, 124–126. https://doi.org/10.1145/3563703.3591452

[14] Neel Dhanaraj, Yeo Jung Yoon, Rishi Malhan, Prahar M. Bhatt, Shantanu Thakar, and Satyandra K. Gupta. 2022. A Mobile Manipulator System for Accurate and Efficient Spraying on Large Surfaces. *Procedia Computer Science* 200 (2022), 1528–1539. https://doi.org/10.1016/j.procs.2022.01.354 3rd International Conference on Industry 4.0 and Smart Manufacturing.

[15] Chris Elsden, Ella Tallyn, and Bettina Nissen. 2020. When do design workshops work (or not)?. In *Companion publication of the 2020 ACM designing interactive systems conference*. Association for Computing Machinery, New York, NY, USA, 245–250. https://doi.org/10.1145/3393914.3395856

[16] Joshua Elsdon and Yiannis Demiris. 2017. Assisted painting of 3D structures using shared control with a hand-held robot. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, IEEE, New York, NY, USA, 4891–4897. https://doi.org/10.1109/ICRA.2017.7989566

[17] Frikk Fossdal, Rogardt Heldal, and Nadya Peek. 2021. Interactive Digital Fabrication Machine Control Directly Within a CAD Environment. In *Symposium on Computational Fabrication*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3485114.3485120

[18] Camila Friedman-Gerlicz, Deanna Gelosi, Fiona Bell, and Leah Buechley. 2024. WeaveSlicer: Expanding the Range of Printable Geometries in Clay. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–16. https://doi.org/10.1145/3613904.3642622

[19] Google. 2022. Google's ARcore: https://developers.google.com/ar. Last accessed August 2022.

[20] Daniel Groeger and Jürgen Steimle. 2018. ObjectSkin: augmenting everyday objects with hydroprinted touch sensors and displays. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 4 (2018), 134. https://doi.org/10.1145/3161165

[21] Ollie Hanton, Mike Fraser, and Anne Roudaut. 2024. DisplayFab: The State of the Art and a Roadmap in the Personal Fabrication of Free-Form Displays Using Active Materials and Additive Manufacturing.. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–24.

[22] Ollie Hanton, Zichao Shen, Mike Fraser, and Anne Roudaut. 2022. FabricatINK: Personal Fabrication of Bespoke Displays Using Electronic Ink from Upcycled E Readers. In *CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–15.

[23] Ollie Hanton, Michael Wessely, Stefanie Mueller, Mike Fraser, and Anne Roudaut. 2020. ProtoSpray: Combining 3D Printing and Spraying to Create Interactive Displays with Arbitrary Shapes. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376543

[24] Tomoko Hashida, Yasuaki Kakehi, and Takeshi Naemura. 2010. Photochromic canvas drawing with patterned light. In *ACM SIGGRAPH 2010 Posters*. Association for Computing Machinery, New York, NY, USA, 1–1. https://doi.org/10.1145/1836845.1836873

[25] Steve Hodges and Mike Fraser. 2022. Citizen Manufacturing: Unlocking a New Era of Digital Innovation. *IEEE Pervasive Computing* 21, 3 (2022), 42–51.

[26] I Hooi, S Oosterholt, S Paschburg, J Phan, N Yeoh, and B Cazzolato. 2010. PICARSO-Programmable interface controller with autonomous robotic spraying operation. *FAO* NA, NA (2010), NA.

[27] Walther Jensen, Ashley Colley, Jonna Häkkilä, Carlos Pinheiro, and Markus Löchtefeld. 2019. TransPrint: A Method for Fabricating Flexible Transparent Free-Form Displays. *Advances in Human-Computer Interaction* 2019 (2019), 1–12. https://doi.org/10.1155/2019/1340182

[28] Yuhua Jin, Isabel Qamar, Michael Wessely, Aradhana Adhikari, Katarina Bulovic, Parinya Punpongsanon, and Stefanie Mueller. 2019. Photo-Chromeleon: Re-Programmable Multi-Color Textures Using Photochromic Dyes. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, Association for Computing Machinery, New York, NY, USA, 701–712. https://doi.org/10.1145/3332165.3347905

[29] Katsu. 2022. KATSU drone project primer. Last accessed September 2022. https://dronegraffiti.tumblr.com/tagged/katsu

[30] Jungha Kim, Minkyeong Song, Yeoeun Lee, Moonkyeong Jung, and Pyojin Kim. 2022. An Empirical Evaluation of Four Off-the-Shelf Proprietary Visual-Inertial Odometry Systems. *arXiv preprint arXiv:2207.06780* NA, NA (2022), NA.
[31] Konstantin Klamka and Raimund Dachselt. 2017. IllumiPaper: Illuminated interactive paper. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, Association for Computing Machinery, New York, NY, USA, 5605–5618. https://doi.org/10.1145/3025453.3025525
[32] Konstantin Klamka, Raimund Dachselt, and Jürgen Steimle. 2020. Rapid Iron-On User Interfaces: Hands-on Fabrication of Interactive Textile Prototypes. In *Proc. CHI*, Vol. 20. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376220
[33] Jarrod Knibbe, Tovi Grossman, and George Fitzmaurice. 2015. Smart Makerspace: An Immersive Instructional Space for Physical Tasks. In *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces* (Madeira, Portugal) *(ITS '15)*. Association for Computing Machinery, New York, NY, USA, 83–92. https://doi.org/10.1145/2817721.2817741
[34] KPT. 2022. KPT EL spraying tutorial. Last accessed August 2025. https://youtu.be/MyyIb8cErag?si=dvAHoHYoN9pGiu8F
[35] Ben Krasnow. 2021. Applied Science Youtube channel. Last accessed September 2021. https://www.youtube.com/watch?v=eUUupR-ongs&t=360s&ab_channel=AppliedScience
[36] lab bubble. 2024. Lab Bubble: https://lab-bubble.com/. Last accessed September 2024.
[37] Markus Lochtefeld, Walther Jensen, and Çaglar Genç. 2021. Prototyping of Transparent and Flexible Electrochromic Displays. In *20th International Conference on Mobile and Ubiquitous Multimedia*. Association for Computing Machinery, New York, NY, USA, 179–181. https://doi.org/10.1145/3490632.3497750
[38] Markus Löchtefeld, Walther Jensen, Çaðlar Genç, and Jonna Häkkilä. 2022. Prototyping and Design of Transparent and Flexible Electrochromic Displays. In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI EA '22)*. Association for Computing Machinery, New York, NY, USA, Article 133, 3 pages. https://doi.org/10.1145/3491101.3503754
[39] Markus Löchtefeld, Walther Jensen, Heiko Müller, and Ashley Colley. 2019. Prototyping Transparent and Flexible Electrochromic Displays. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–4. https://doi.org/10.1145/3290607.3298827
[40] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600
[41] Pedro Lopes, Doǎa Yüksel, François Guimbretière, and Patrick Baudisch. 2016. Muscle-plotter: An interactive system based on electrical muscle stimulation that produces spatial output. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 207–217. https://doi.org/10.1145/2984511.2984530
[42] Joseph Luk. 2004. Computer-controlled airbrush with motion tracking. *Dept. Computer Science, Univ. British Columbia* 1, 1 (2004), 1–5.
[43] LumiLor. 2019. Electroluminescent paint: https://www.lumilor.com/. Last accessed August 2025.
[44] LumiLor. 2022. Lumilor Basics and FAQ. Last accessed August 2025. https://support.lumilor.com/en/article/lumilor-basics-and-faq
[45] LumiLor. 2022. Lumilor Pro Specifications: https://www.ellumiglow.com/differences-between-lumilor-and-lumilor-pro-el-paint-applications. Last accessed August 2025.
[46] LumiLor. 2022. Lumilor Training video. Last accessed August 2025. https://www.youtube.com/watch?v=78iRCkDva00&ab_channel=LumiLor
[47] Kartik Madhira, Sandip Mehta, Rahul Bollineni, and Dishant Kavathia. 2017. AGWallP—Automatic guided wall painting system. In *2017 Nirma University International Conference on Engineering (NUiCONE)*. IEEE, Association for Computing Machinery, New York, NY, USA, 1–5. https://doi.org/10.1109/NUICONE.2017.8325614
[48] Miro. 2022. Miro: https://miro.com/app/dashboard/. Last accessed August 2022.
[49] Kongpyung Moon, Zofia Marciniak, Ryo Suzuki, and Andrea Bianchi. 2024. 3D Printing Locally Activated Visual-Displays Embedded in 3D Objects via Electrically Conductive and Thermochromic Materials. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–15.
[50] Motorola. 2022. Motorola G50 Phone: https://www.motorola.co.uk/smartphones-moto-g-50/p. Last accessed August 2022.
[51] Ilan E Moyer, Samuelle Bourgault, Devon Frost, and Jennifer Jacobs. 2024. Throwing Out Conventions: Reimagining Craft-Centered CNC Tool Design through the Digital Pottery Wheel. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–22. https://doi.org/10.1145/3613904.3642361
[52] Stefanie Mueller, Laura Devendorf, Stelian Coros, Yoichi Ochiai, Madeline Gannon, and Patrick Baudisch. 2016. CrossFAB: Bridging the Gap between Personal Fabrication Research in HCI, Computer Graphics, Robotics, Art, Architecture, and Material Science.. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 3431–3437.
[53] Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch. 2014. WirePrint: 3D printed previews for fast prototyping. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. Association for Computing Machinery, New York, NY, USA, 273–280. https://doi.org/10.1145/2642918.2647359
[54] Stefanie Mueller, Pedro Lopes, and Patrick Baudisch. 2012. Interactive construction: interactive fabrication of functional mechanical devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*. Association for Computing Machinery, New York, NY, USA, 599–606.
[55] Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: fabricating highly customizable thin-film touch-displays. In *Proceedings of the 27th annual ACM symposium on User interface software and technology*. ACM, Association for Computing Machinery, New York, NY, USA, 281–290. https://doi.org/10.1145/2642918.2647413
[56] Optomec. 2022. Optomec 3D aerosol printer: https://optomec.com/. Last accessed September 2022.
[57] Joyce E Passananti, Ana CardenasGasca, Jennifer Jacobs, and Tobias Höllerer. 2023. SculptAR: Direct Manipulations of Machine Toolpaths in Augmented Reality for 3D Clay Printing. In *Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 1–3. https://doi.org/10.1145/3586182.3615822
[58] Roshan Lalintha Peiris and Ryohei Nakatsu. 2013. TempTouch: A Novel Touch Sensor Using Temperature Controllers for Surface Based Textile Displays. In *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces* (St. Andrews, Scotland, United Kingdom) *(ITS '13)*. Association for Computing Machinery, New York, NY, USA, 105–114. https://doi.org/10.1145/2512349.2512813
[59] Huaishu Peng, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. RoMA: Interactive fabrication with augmented reality and a robotic 3D printer. In *Proceedings of the 2018 CHI conference on human factors in computing systems*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174153
[60] Narjes Pourjafarian, Marion Koelle, Fjolla Mjaku, Paul Strohmeier, and Jürgen Steimle. 2022. Print-A-Sketch: A Handheld Printer for Physical Sketching of Circuits and Sensors on Everyday Surfaces. In *CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–17. https://doi.org/10.1145/3491102.3502074
[61] Romain Prévost, Alec Jacobson, Wojciech Jarosz, and Olga Sorkine-Hornung. 2016. Large-scale painting of photographs by interactive optimization. *Computers & Graphics* 55 (2016), 108–117. https://doi.org/10.1016/j.cag.2015.11.001
[62] Parinya Punpongsanon, Xin Wen, David S Kim, and Stefanie Mueller. 2018. ColorMod: Recoloring 3D Printed Objects using Photochromic Inks. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, Association for Computing Machinery, New York, NY, USA, 213. https://doi.org/10.1145/3173574.3173787
[63] Isabel PS Qamar, Rainer Groh, David Holman, and Anne Roudaut. 2018. HCI meets material science: A literature review of morphing materials for the design of shape-changing interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–23.
[64] Alec Rivers, Ilan E. Moyer, and Frédo Durand. 2012. Position-Correcting Tools for 2D Digital Fabrication. *ACM Trans. Graph.* 31, 4, Article 88 (jul 2012), 7 pages. https://doi.org/10.1145/2185520.2185584
[65] Daniela K Rosner, Saba Kawas, Wenqi Li, Nicole Tilly, and Yi-Chen Sung. 2016. Out of time, out of place: Reflections on design workshops as a research method. In *Proceedings of the 19th ACM Conference on Computer-Supported Cooperative Work & Social Computing*. Association for Computing Machinery, New York, NY, USA, 1131–1141. https://doi.org/10.1145/2818048.2820021
[66] Thijs Roumen, Bastian Kruck, Tobias Dürschmid, Tobias Nack, and Patrick Baudisch. 2016. Mobile fabrication. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 3–14. https://doi.org/10.1145/2984511.2984586
[67] Rei Sakura, Changyo Han, Yahui Lyu, Keisuke Watanabe, Ryosuke Yamamura, and Yasuaki Kakehi. 2023. LattiSense: A 3D-Printable Resistive Deformation Sensor with Lattice Structures. In *Proceedings of the 8th ACM Symposium on Computational Fabrication*. Association for Computing Machinery, New York, NY, USA, 1–14.
[68] Andreas Sandström, Amir Asadpoordarvish, Jenny Enevold, and Ludvig Edman. 2014. Spraying Light: Ambient-Air Fabrication of Large-Area Emissive Devices on Complex-Shaped Surfaces. *Advanced Materials* 26, 29 (2014), 4975–4980. https://doi.org/10.1002/adma.201401286
[69] Valkyrie Savage, Xiaohan Zhang, and Björn Hartmann. 2012. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. In *Proceedings*

of the 25th annual ACM symposium on User interface software and technology. ACM, Association for Computing Machinery, New York, NY, USA, 579–588.

[70] Tim Scargill, Jiasi Chen, and Maria Gorlatova. 2021. Here to stay: Measuring hologram stability in markerless smartphone augmented reality. *arXiv preprint arXiv:2109.14757* NA, NA (2021), NA.

[71] Sceneform. 2022. Communtiy Maintained Sceneform. Last accessed August 2022. https://github.com/SceneView/sceneform-android

[72] Martin Schmitz, Mohammadreza Khalilbeigi, Matthias Balwierz, Roman Lissermann, Max Mühlhäuser, and Jürgen Steimle. 2015. Capricate: A fabrication pipeline to design and 3D print capacitive touch sensors for interactive objects. *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* 1, 1 (2015), 253–258. https://doi.org/10.1145/2807442.2807503

[73] Eldon Schoop, Michelle Nguyen, Daniel Lim, Valkyrie Savage, Sean Follmer, and Björn Hartmann. 2016. Drill Sergeant: Supporting physical construction projects through an ecosystem of augmented tools. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1607–1614. https://doi.org/10.1145/2851581.2892429

[74] Stefano Seriani, A Cortellessa, S Belfio, M Sortino, G Totis, and Paolo Gallina. 2015. Automatic path-planning algorithm for realistic decorative robotic painting. *Automation in Construction* 56 (2015), 67–75. https://doi.org/10.1016/j.autcon.2015.04.016

[75] Jenna M Shapiro, Bruce W Drinkwater, Adam W Perriman, and Mike Fraser. 2021. Sonolithography: In-Air Ultrasonic Particulate and Droplet Manipulation for Multiscale Surface Patterning. *Advanced Materials Technologies* 6, 3 (2021), 2000689.

[76] Roy Shilkrot, Pattie Maes, Joseph A Paradiso, and Amit Zoran. 2015. Augmented airbrush for computer aided painting (CAP). *ACM Transactions on Graphics (TOG)* 34, 2 (2015), 19. https://doi.org/10.1145/2699649

[77] Carter Slocum, Xukan Ran, and Jiasi Chen. 2021. RealityCheck: A tool to evaluate spatial inconsistency in augmented reality. In *2021 IEEE International Symposium on Multimedia (ISM)*. IEEE, Association for Computing Machinery, New York, NY, USA, 58–65.

[78] Marc Steen. 2008. The fragility of human-centred design. *TNO* 1, 1 (2008), 1–18.

[79] S-H Suh, I-K Woo, and S-K Noh. 1991. Development of an automatic trajectory planning system (ATPS) for spray painting robots. In *Proceedings. 1991 IEEE International Conference on Robotics and Automation*. IEEE, ieeexplore.ieee.org, ., 1948–1955. https://doi.org/10.1109/ROBOT.1991.131912

[80] Haruki Takahashi and Jeeeun Kim. 2019. 3D pen+ 3D printer: Exploring the role of humans and fabrication machines in creative making. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300525

[81] Rundong Tian and Eric Paulos. 2021. Adroid: Augmenting Hands-on Making with a Collaborative Robot. In *The 34th Annual ACM Symposium on User Interface Software and Technology* (Virtual Event, USA) *(UIST '21)*. Association for Computing Machinery, New York, NY, USA, 270–281. https://doi.org/10.1145/3472749.3474749

[82] Rundong Tian, Vedant Saran, Mareike Kritzler, Florian Michahelles, and Eric Paulos. 2019. Turn-by-wire: Computationally mediated physical fabrication. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 713–725. https://doi.org/10.1145/3332165.3347918

[83] Tsuru. 2022. Tsuru drone project: https://tsuru.su/en/project/spritemural/. Last accessed September 2022.

[84] Anastasia Uryasheva, Mikhail Kulbeda, Nikita Rodichenko, and Dzmitry Tsetserukou. 2019. DroneGraffiti: autonomous multi-UAV spray painting. In *ACM SIGGRAPH 2019 Studio*. Association for Computing Machinery, New York, NY, USA, 1–2.

[85] Anurag Sai Vempati, Mina Kamel, Nikola Stilinovic, Qixuan Zhang, Dorothea Reusser, Inkyu Sa, Juan Nieto, Roland Siegwart, and Paul Beardsley. 2018. Paintcopter: An autonomous uav for spray painting on three-dimensional surfaces. *IEEE Robotics and Automation Letters* 3, 4 (2018), 2862–2869.

[86] Yue Wang, Liangxi Xie, Hao Wang, Wenhao Zeng, Yonghui Ding, Teng Hu, Tao Zheng, Hongyu Liao, and Jing Hu. 2022. Intelligent spraying robot for building walls with mobility and perception. *Automation in Construction* 139 (2022), 104270. https://doi.org/10.1016/j.autcon.2022.104270

[87] Christian Weichel, John Hardy, Jason Alexander, and Hans Gellersen. 2015. ReForm: Integrating Physical and Digital Design through Bidirectional Fabrication. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology* (Charlotte, NC, USA) *(UIST '15)*. Association for Computing Machinery, New York, NY, USA, 93–102. https://doi.org/10.1145/2807442.2807451

[88] Christian Weichel, Manfred Lau, David Kim, Nicolas Villar, and Hans W Gellersen. 2014. MixFab: a mixed-reality environment for personal fabrication. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 3855–3864. https://doi.org/10.1145/2556288.2557090

[89] Michael Wessely, Yuhua Jin, Cattalyya Nuengsigkapian, Aleksei Kashapov, Isabel PS Qamar, Dzmitry Tsetserukou, and Stefanie Mueller. 2021. ChromoUpdate: Fast Design Iteration of Photochromic Color Textures Using Grayscale Previews and Local Color Updates. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, 1–13.

[90] Michael Wessely, Ticha Sethapakdi, Carlos Castillo, Jackson C. Snowden, Ollie Hanton, Isabel P. S. Qamar, Mike Fraser, Anne Roudaut, and Stefanie Mueller. 2020. Sprayable User Interfaces: Prototyping Large-Scale Interactive Surfaces with Sensors and Displays. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376249

[91] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2016. Stretchis: Fabricating Highly Stretchable User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 697–704. https://doi.org/10.1145/2984511.2984521

[92] Karl DD Willis, Cheng Xu, Kuan-Ju Wu, Golan Levin, and Mark D Gross. 2010. Interactive fabrication: new interfaces for digital fabrication. In *Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*. ACM, New York, NY, USA, 69–72.

[93] Paris Xyntarianos-Tsiropinas, Thomas Spyrou, and Konstantinos Bailas. 2018. Using Design to Support the Creation of Street Art: A three-phase experiment supported by the DDArtS system Paris. *Electronic Visualisation and the Arts* NA, NA (2018), 272–279.

[94] Yang Zhang, Chouchang (Jack) Yang, Scott E. Hudson, Chris Harrison, and Alanson Sample. 2018. Wall++: Room-Scale Interactive and Context-Aware Sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–15. https://doi.org/10.1145/3173574.3173847

[95] Wenda Zhao, Muhammad Yasir Khan, Daniele Baiocco, Zhibing Zhang, and Anne Roudaut. 2025. Ecolor: Synthesis of EInk Microcapsules for Fabricating DIY Displays. In *Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 1–20.

[96] Bo Zhou, Xi Zhang, Zhengda Meng, and Xianzhong Dai. 2014. Off-line programming system of industrial robot for spraying manufacturing optimization. In *Proceedings of the 33rd Chinese Control Conference*. Association for Computing Machinery, New York, NY, USA, 8495–8500. https://doi.org/10.1109/ChiCC.2014.6896426

[97] Yunyi Zhu, Cedric Honnet, Yixiao Kang, Junyi Zhu, Angelina J Zheng, Kyle Heinz, Grace Tang, Luca Musk, Michael Wessely, and Stefanie Mueller. 2024. PortaChrome: A Portable Contact Light Source for Integrated Re-Programmable Multi-Color Textures. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3654777.3676458

[98] Amit Zoran and Joseph A. Paradiso. 2013. FreeD: A Freehand Digital Sculpting Tool. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 2613–2616. https://doi.org/10.1145/2470654.2481361