The Development and (Mis)appropriation of a Digital Kit for Jewellers

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The Development and (Mis)appropriation of a Digital Kit for Jewellers

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Jewellers' participation in interaction design is scarce, yet the creativity of jewellers could add value as they interpret materials and mediate personal connections in poetic ways. We investigate how to empower jewellers to experiment with the possibilities that physical computing offers to their practice. This article presents the making of a Digital Jewellery Kit, a composite of pre-assembled circuitry, used by second-year BA jewellery students during a 10-week project which brought together theory and practice. Drawing on students' reflective accounts, we discuss what made the jewellers' path into physical computing more meaningful to their practice, what type of artefacts they created with electronics as well as what values drove their creative process. We offer design recommendations on how to support the praxes of jewellers whilst allowing their creativity to grow through their new understanding of physical computing and contribute to the discussions around hybrid craft within HCI and educational contexts.

CCS Concepts: • **Human-centered computing → Interaction design theory, concepts and paradigms**;

Additional Key Words and Phrases: digital jewellery, wearable technology, electronics, craft practice, physical computing

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1 Introduction

Jewellery is an ancient cross-cultural practice that creates precious artefacts to be worn on the body and clothes. Archaeological findings and historical sources have shown that jewellery has been used for multiple purposes: as functional items (e.g. to fasten clothes), to show status and belonging (e.g. marital and social), as talisman and protection, as a carrier of personal meaning, and in religious rituals. This definition is still valid today with contemporary jewellery using a wide range of materials, from precious metalwork to 3D printed structures, for an equivalent wide range of uses and symbolism.

Jewellery education still lacks appreciation for the digital as material for design in contemporary jewellery making. This attitude contrasts with the breadth of creative practices blooming within fashion and physical computing which has resulted in established communities of makers who explore the intersection of clothing, textiles and technology with a creative eye [23, 65, 72]. The crossing of fashion and computing is now reflected in many universities offering 'fashion-tech' as part of their programme of study. Instead, the creative practices of jewellers working with electronics are still limited to a few researchers. Yet, the creativity of jewellers holds huge potential for shaping the future of how technology and wearable objects intersect. Currently, the wearable technology industry sees the contribution of jewellery as mere 'beautification' of technological devices, such as fitness trackers or health monitors, failing to appreciate the deep understanding jewellers have of the personal and intimate connections of devices to the body. Within **Human-Computer Interaction (HCI)**, Digital Jewellery is mostly seen as a subset of wearable technology and jewellery has been researched predominantly as a tangible input device to generate and control interaction [20, 42]. Jewellers can bring a fresh perspective to both the wearable industry and HCI research as they have a deep understanding of how personal objects 'vehiculate' and materialise identity, and have the skills and expertise to create objects that transmit value [30]. In other words, jewellers make human values tangible through materials. Through their close engagement with the conceptual narratives inherent in their discipline, jewellers gain an awareness of the ethical, societal and cultural implications of their design, while the embodied knowledge that comes from handling a broad variety of materials can be applied to create highly individualised aesthetic artefacts with layers of meaning [8, 19, 25, 51, 53].

Although jewellery education is lagging behind, a few jewellery practitioner-researchers have been experimenting with digital technology to explore how to add layers of meaning and enrich the wearer's experience through digital interaction. These interactive artefacts have been called 'digital jewellery' [80, 82], 'smart jewellery' [78] or 'interactive jewellery' [77], terms used interchangeably to refer to the emerging field of research that combines microelectronics and digital technology with jewellery practices. We use the term 'digital jewellery' to mean the aesthetic-led jewellers' approach to the design of digital devices on and in relation to the body. Electronic components such as sensors, GPS and WiFi connectivity offer new interpretations of the intimate connection between jewellery and the human body, e.g. an affective cardiac monitoring [37]; a playful interaction between people and objects [78]; personally significant data accessed in poetic, non-numeric ways [49]; digital memories stored in personal objects (e.g., rather than social media or on cloud archives) [81]; and addressing loneliness [36]. These remarkable examples show that digital technology and data hold a huge potential within jewellery practice to explore a highly personal yet complex design space at the intersection of art, craft, design and technology.

In light of this research, we situate digital jewellery practice as an extension of the jewellers' toolbox to move the jewellery discipline into contemporary digital society with the addition of the digital material. Like jewellery, digital jewellery encompasses socio-cultural aspects of status, identity and ritual through the combination of materials that represent the interconnection between people, objects and places.

This research starts from these premises and argues that there is value in facilitating jewellers' understanding and use of physical computing, as they could play an important role in shaping the future of the discipline and inform wearables research more broadly. Our main aim is to empower jewellers to experiment with the possibilities that wearable and digital technology offer to their practice and answer the following questions:

What would make the jewellers' path into physical computing more meaningful to their practice?
How do electronics and interaction design affect or even change the aesthetics of jewellery?
What type of digital artefacts would jewellers create?
What values would drive their creative process?

Our study sits in the research area that explores and experiments with electronics as material for design [7, 41, 59, 83]. Our aim is to ease the entry of jewellers into the world of physical computing and inspire them to think of meaningful contexts for their creations. For this purpose, we created a Digital Jewellery Kit that enables creatives to get started with physical computing using pre-assembled circuitry and inspirational examples informed by existing research in digital jewellery.

The kit and the complementary resources at the centre of this article were used by 14 BA second-year jewellery students over a period of 10 weeks to create their own original artefact as part of their course assignment. In following an action research methodology (plan, act, observe, reflect), we offer an account of our process of designing the kit and the associated resources, how students reacted to the activities intended to familiarise them with the basics of physical computing, and how they assimilated computing concepts to appropriate the kit. Our contribution is a deeper understanding of how jewellery makers learn to engage with the digital as material. By doing so, we take a closer look at the new and changing materiality of jewellery practice induced by the miniaturisation of electronics. The students' final pieces challenge the existing boundaries between digital devices and jewellery and contribute exemplars that embody new thinking and directions in the field of digital jewellery. The role of second-year students as actors in the research is important: they are learning how to handle a range of new materials such as precious metals and stones, ceramic, leather and wood. Digital technology was introduced as just another material for them to learn and experiment with. Throughout the article, we use the term 'creatives' to refer to both practitioners without computing skills (low or no understanding of electronics or coding) as well as to practitioners with a negative attitude towards learning computing (see it as irrelevant). In both cases, the result is a lack of digital material within their practice. In contrast, we use the term 'digital creatives' to refer to those creatives with a positive attitude towards and competence in computing.

The article is organised as follows: In the next section, we review the literature on electronic prototyping tools for creatives and the material practices embraced by the DIY culture. Section 3 discusses the action research methodology and how we applied it. Sections 4 to 7 describe each step of the action research in detail, namely: *plan*—the design and development of the prototypes included in the kit; *act*—the 10-week project; *observe*—the students' annotated sketchbooks and final pieces; *reflect*—our reflection on the whole process. By studying the students' work and through a design critique of a selection of their final artefacts we discuss our findings in Section 8 and offer takeaways for the future development of digital toolkits for jewellers and how to foster a fruitful collaboration between HCI and jewellers.

Overall, this research shows opportunities for pedagogical practices by extending prior research in HCI to digital jewellery. The explorations and outcomes of the students' projects demonstrate how creatives can change the way in which electronics manifests itself; this, in turn, can inform and inspire future directions in the domain of teaching physical computing when the aim is to go beyond the learning of computing skills. Therefore, the design considerations suggested in this article, while being a solid starting point to teach physical computing to jewellers, offer valuable lessons for those developing toolkits and learning materials for physical computing in general. In addition, the article contributes to the research done at the intersection between craft practice and interaction design. Specifically, we offer practical and theoretical recommendations to HCI researchers working on wearables and encourage them to include digital jewellery in their work as jewellers bring their unique perspective on traditional materials (metal, gems, wood, fabric, leather) and transform digital materials through their experiential, hands-on approach. In essence, digital jewellery can bring new creative power in the context of tangible interaction design and hybrid crafting.

2 Background

2.1 Toolkits to Explore Physical Computing

A common approach in developing toolkits for creatives with no experience in coding or interest in learning computing is to completely conceal electronics. ‘Blackboxing’, as a design philosophy, separates users from the system [57] by presenting pre-assembled sensors and actuators to demystify technology and physical computing. Thus, *blackbox* toolkits lower the entry level for beginners interested in exploring the interactive possibilities of electronics without the need to learn to code. For example, with complete beginners in mind, the designers of the Smörgåsbords [9] deliberately left out elements of programming and wiring electronics to offer product design students a range of interactions to be used in the ideation phase. LittleBits (plug and play) [7], Wearable Bits [43] and Snowflakes [16] target creatives with no coding experience and invite them to move from ideation to prototyping. LittleBits have been used within digital jewellery education in 1-day ideation workshops to explore interactions with light [2], yet this research did not investigate students’ understanding of the digital as material. Snowflakes enabled creatives to explore jewellery-specific interactions by connecting flexible blocks to create wearable pieces [16]. Similar to LittleBits, Wearable Bits supports prototyping and basic interactions with soft wearable components by means of reusing templates [43]. Overall, while ‘blackboxing’ allows creatives with no experience or interest in learning electronics and coding to use sensors and actuators, the expressivity of what they can create is limited to the (simple) interactions and materials chosen by the toolkit’s designers.

Up a level from blackboxes, *modular kits* simplify complex computing processes but still require some programming knowledge and basic electronics skills in return for more room to prototype articulated interactions. For example, Tiles that Talk [10] is a kit for art students to easily implement network connections, and in Aniomagics Chiclets [27] users assemble a bracelet using pre-set components to be (re)programmed through a graphical interface synchronised with tapping on the components. Another example is the WearEC kit [32] to explore specific interactions with electrochromic displays on the body. These modular kits are of interest to jewellers wishing to understand interactions by putting together and taking apart electronics, a process described within the framework of constructive assemblies [50]. Modular kits enable users to create more complex interactions than blackboxing, but still within the limitations of the hardware available (e.g. network connectivity).

Higher in the level of computing and electronics knowledge required to get started are off-the-shelf *DIY kits*. Different kits require different levels of programming skills and offer different levels of articulated interactions depending on the hardware used. Examples are the two historical wearable construction kits LilyPad [14] and Flora [71] that broadened wearable creation by empowering non-engineers to create computational designs on the body. Such kits have been widely used for e-textiles and come in a variety of forms of microcontrollers and components such as conductive threads and sewable sensors. As general-purpose boards, they are used to assemble an artefact with a specific function, each artefact using the same board with different sensors for different interactions. Despite their success in the maker community, these kits require an understanding of circuits and coding, a knowledge and an attitude that is less common among creatives.

Another group of boards with in-built sensors can be coded using visual blocks interfaces (*block coding board*). For example, BBC micro:bit [54] or the Circuit Playground Express from Adafruit [1] have many in-built hardware components (e.g. LEDs, buttons, accelerometer, compass, temperature and light sensors), a visual programming language to code them with, and an easy way to upload it onto the device. Programming these boards is simpler, but still requires some understanding of computing concepts to troubleshoot. Indeed, these boards are targeted to those who want to learn computing. The Grove Beginner Kit for Arduino from Seeed Studio [39] further simplifies the hardware assembly by offering one board with pre-assembled electronics; however, it is not targeted to creatives interested in craft practices and still requires a good level of programming.

In summary, blackbox toolkits that completely conceal electronics are the easiest to use but constrain creativity; modular kits simplify complex interactions but require a basic level of computing and electronics; and DIY toolkits for learning basic computing (i.e., Arduino, Adafruit, Seeeduino) are very flexible but require an understanding of coding. Creatives with no knowledge of computing nor an interest in it could find blackbox toolkits ideal, yet the limitations blackboxing imposes on what concepts could be implemented is likely to frustrate creatives, as our work shows. With modular and DIY kits, creatives must first deal with the complexities of learning computing and coding before they can bring in their creative skills, thus they may not see the value of learning computing. We believe the craft and aesthetics of the final outcomes are major factors [43, 62] when developing tools for creatives. Therefore, it is essential to strike the right balance between ease-of-use and creative freedom. Finding this balance is what we investigated in our study of introducing jewellers to physical computing. As discussed in detail in Section 3.1, we started by creating a blackbox kit to later realise that students' creativity was hampered by a limited choice and shifted our approach towards a block coding board.

2.2 Material Practices

It could be argued that toolkits are not needed and that the DIY culture could supply the explicit knowledge to navigate the complexities of working with digital technology and electronics with the support of an open source community. Instructables is a website focused on DIY projects which offers a plethora of tutorials and how-to pages including examples of digital jewellery making spanning from intricate free-form electronics (i.e., free-formed solar chirping bird pendant[1]), to material explorations with electronics (i.e., growing crystals on LEDs[2]), to simple circuits that tell stories (i.e., telegraph pendant[3]). Such examples intend to inspire and guide the making step-by-step with descriptive instructions. However, it has been argued that the information is often unclear, hard to follow and rarely complete, [22, 79] leaving in place the 'technical barriers' that prevent users with no technical knowledge, especially jewellers, from becoming part of this community. Cases of two strong open source communities are those connected to Adafruit and Sparkfun. The artistic community of Adafruit offers examples of wearable projects for all levels supporting the approach to programming-by-demonstration [4]. However, the examples from the makers' communities focus on the how-to, quickly moving into prototyping while the maker's design considerations that informed their materials practices are often undocumented.

A more radical approach is the 'un-tool-kit' in which flexible sensors and circuits are crafted with paper and conductive ink [52] and the 'kit of no parts' approach to computing, where individual

[1]https://www.instructables.com/Free-Formed-Solar-Chirping-Bird-Pendant-Using-0603/
[2]https://www.instructables.com/Growing-Crystals-on-LEDs-and-ETextiles/
[3]https://www.instructables.com/Telegraph-Pendant/

soft sensors and components are handmade with craft materials [60]. Joining this philosophy within the jewellery discipline, Tsaknaki et al. [76] create switches using silversmithing techniques. Such radical approaches leverage the affordances of material practices embedded within textiles or silversmithing and offer creative possibilities to a craft-computing practice. The outcome is a unique artefact where the electronics cannot be taken apart from the piece itself: the electronic circuitry is itself the piece. The iterative design happens by starting anew, an action more akin to that of an artist, setting aside one sketch and beginning another [60]. These alternative forms of electronics tinkering are completely flexible and eschew the pre-made ecosystem of commercially manufactured components, bringing the making of electronic circuits an integral part of the craft [57]. The making of bespoke sensors using a specific craft is fascinating and promising, but still far from being applicable in a wider context where multiple sensors and actuators are needed to create meaningful interactions.

To conclude, our ambition is to inspire jewellers to make interactive and meaningful artefacts, rather than to learn computing which is often the implicit goal with most kits in this domain. This is in line with some long-standing discussions in the area of children's programming, i.e. providing tools to allow them to participate in contemporary culture [28] versus making games as a means to learn mathematics [58]. We started this research with the belief that digital resources for jewellers with no previous knowledge of electronics and computing should aim at ease-of-use while maintaining a wide-open creative aspect (as discussed in Section 2.1). Blackbox toolkits are useful at the ideation stage and the initial engagement with physical computing. Later in the creative process, block coding board toolkits for learning basic programming and circuit-building skills provide the needed flexibility while requiring a low entry level. Creatives may not see the value of learning basic computing skills as important; yet our study showed it was an essential step to be able to make what they imagined rather than what the blackbox allowed them to do. Finally, examples such as those offered by the DIY community were valuable as inspiration and to build the creatives' confidence in completing the challenging task of creating a piece of a meaningful piece of digital jewellery.

3 Research Rationale and Methodology

To answer the research questions, we articulate the research in the four phases of *action research*: *plan*—we first conceptualised, designed and developed the digital kit and the resources we intended to use over the 10-week program; *act*—students worked with the resources to create their own final pieces; *observe*—we observed the students at work, examined their annotated sketchbooks and their final pieces; *reflect*—we reflected on the use of the resources we created to derive lessons for the future. An established methodology used in both computer science [6] and the humanities, e.g. in education [70], action research aims to provoke change in the current situation supported by empirical evidence. This section gives a brief overview of the action research methodology by articulating the four phases before discussing each one in detail in the next four sections.

3.1 Planning

The circuitry and the complementary resources we created derive from theories and knowledge consolidated in the research community. We authors have years of experience in digital jewellery research and practice, interaction design and computing. Brainstorming, experience sharing and open discussions among the members of the team informed the design and building of the pre-assembled circuits, each with a specific interaction concept (Table 1). We aimed to reduce (ideally to eliminate) the complexity that working with electronics poses to absolute beginners. We intended to push jewellery students with no prior knowledge of electronics or coding to reflect on the properties of electronics and to start experimenting with their own ideas, forms and personal meanings. We did not expect or want jewellery students to learn computer programming. We wanted them

Table 1. The Concepts and Circuitry of the Digital Jewellery Kit

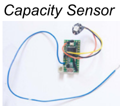
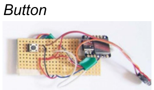
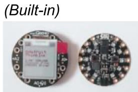
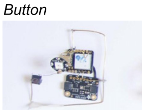
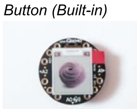
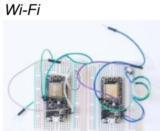
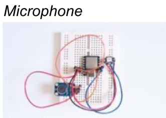
Input	Output	Prototypes	Concept/Interaction	Electronics Used
Capacity Sensor 	LED	*Sensing Touch*	When the sensor records a touch above a set threshold, the LED lights up smoothly. The LED slowly fades out when the value decreases below the threshold.	Teensy 3.2 Flora RGB Smart NeoPixel version 2
Temperature Sensor Button 	LED	*Sensing Temperature*	The wearer sets the threshold by pressing the button. The sensor measures the temperature. When the temperature is within range (+ or − 2 degrees from the threshold) the LED is on. A change in temperature shows as light fading in and out.	Seeeduino XIAO Adafruit BME688—Temperature, Humidity, Pressure and Gas Sensor—STEMMA QT Flora RGB Smart NeoPixel version 2
Light Sensor (Built-in) 	E-Ink screen	*Sensing Light or Darkness*	The screen displays only two images. When the sensor detects light or darkness, the image on the screen changes.	Circuit Playground Express Circuit Playground Tri-Color E-Ink Gizmo
Altimeter Sensor Button 	LED	*Sensing Height*	The wearer sets the threshold by pressing the button. The sensor measures the altitude. When the altitude is within range (+ or − 2 m from the threshold) the LED is on. A change in altitude shows as light fading in and out.	Seeeduino XIAO Adafruit BMP388—Precision Barometric Pressure and Altimeter Flora RGB Smart NeoPixel version 2
Button (Built-in) 	E-Ink screen	*Selected Images*	When the button is pressed, one of the three images is shown. The image can be changed only after 2 minutes (hardware constraint).	Circuit Playground Express Circuit Playground Tri-Color E-Ink Gizmo
Connected devices *Wi-Fi* 	LED	*Connected Brooches (Switch)*	When two people wear two brooches in different locations, both brooches light up. In any other occasion the LEDs remain off. The piece does not have a button. The act of pinning the brooch activates the interaction.	2 × Adafruit Feather HUZZAH with ESP8266 WiFi 2 × Flora RGB Smart NeoPixel
Bluetooth 	matrix of LED	*Connected Brooches (Proximity)*	When the Bluetooth signal's strength drops it triggers an alert signal of vibration and flashing lights.	2 × Micro:bit + MakeCode.com
Microphone 	LED	*Sensing Blowing*	When the wearer moves close and blows on the piece, the LED turns on/off with a smooth transition (fade in/out).	Seeeduino XIAO Adafruit Electret Microphone Amplifier Flora RGB Smart NeoPixel version 2
Magnetometer 	matrix of LEDs	*Pointing North*	When the piece points north, the LED matrix displays a 'N'.	Micro:bit + Makecode.com

Table 2. The Structure of Activities during the 10-Week Project

Activities	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10
Visual Research: Poetic Objects	■									
Theory: Lectures and Examples		■				■				
Practical: Physical Computing		■	■							
Show and Tell: Mixing Physical and Digital				■						
Tutorials and Design Development			■		■		■		■	■
Design Crits	■			■					■	■
Workshops: Ways of Making			■	■	■		■	■		

to appreciate how electronics can augment jewellery practice, to experiment and explore what electronics combined with other materials could be, and to use electronics in a meaningful way as part of their final project. To scaffold students' approach to physical computing, we developed a range of lectures and activities (Table 2). Therefore, with the term 'Digital Jewellery Kit' we mean both the set of the pre-assembled circuity and other resources such as design examples, lectures and practical workshops.

3.2 Acting

Building on the ethos of the studio practice as an effective approach to learning and teaching [21], we invited students to explore digital as a material through hands-on experimentation and interaction with peers. For clarity, studio refers to the physical space where students and tutors meet to engage in conversations and making practices; it is an established approach to teaching in art, design and architecture education which embraces thinking through making [21, 40]. In the studio, we discussed research artefacts that question and critique the use of technology. Lectures in class introduced principles of interaction design and digital jewellery. Practical workshops with electronics (micro:bit in Table 1) and materials other than metal such as ceramic, wood and 3D printing complemented and completed the range of activities in the program of study. While preparing the range of seminars, hands-on activities, group critiques and discussions we were aware of the difficulties of introducing jewellers to electronics and coding while leaving them free to explore and experiment. Our students had no prior knowledge of electronics or coding and were sceptical that electronics could add anything of value to their future profession. Thus, we needed to overcome the students' doubts about the value of digital as an important aspect of their making practices while inspiring and guiding their use of electronics as a new material.

3.3 Observing

The prototypes and the resources created were used by 14 second-year BA jewellery students over a period of 10 weeks to create a piece of digital jewellery holding an emotional value. The student cohort was composed of five UK and seven international students aged 19–25 plus two UK mature students. The mature students encountered difficulties in using computers prior to the digital jewellery project, which added an initial barrier to understanding the brief. As part of their assignment, students had to record their progress in an annotated sketchbook (Figure 1) as well as to participate in group discussions and studio activities. An annotated Sketchbook is a visual document that includes students' narratives on their work. Like 'Learning Journals' [55] and 'Learning Portfolios' [85], annotated sketchbooks document students' design process and capture personal reflections around their learning practice. The discursive writing style alongside the visual content is an ideal tool for design educators to evaluate students' learning through the evidence provided (Figure 1). Moreover, the personal narratives were central to the thematic analysis as that text was key to interpret the visual documentation (photos of the experiments and

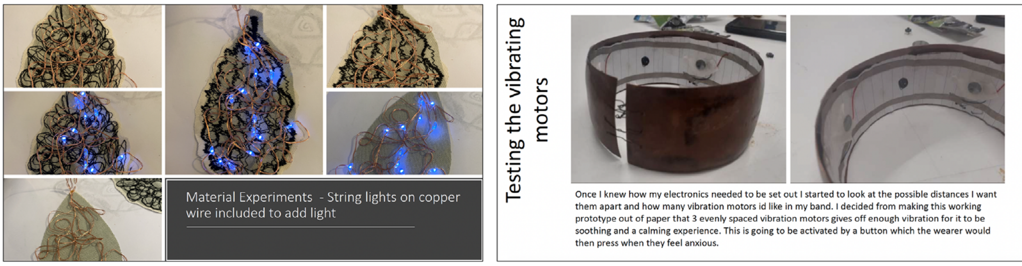


Fig. 1. Two examples of students' annotated sketchbook: (left) Louise[4] documents how she explored materials and interactions to inform her design practice; (right) Alice reports the development of her project on how vibration motors would be set in the jewellery form.

prototypes). These narratives evidenced students' material and digital explorations, their increasing understanding of computing and their design decision to keep or abandon a concept. This is an essential part of action research as the students' explorations and reflections generate data that capture both the successes and failures of our interventions. We expected students' individual sensitivity as makers would emerge from their sketchbooks as they appropriate the same technology in different ways to create their own pieces. By bringing in their individual practice and creativity, students' work multiplies the possibilities of digital jewellery, illustrating different ways in which the same electronics could be appropriated. With their practice, students became co-creators of meanings as their artefacts became material for knowledge generation.

Over the course of the 10 weeks, we observed the students' creative development as it unfolded during informal discussions in the studio, in students' annotated sketchbooks and experientially in the act of making digital jewellery. Feedback was continuously available to students during the 10 weeks. For the formal course assessment, we reviewed the students' sketchbooks and physical pieces at the mid-point and at the end of the project. This process allowed us to observe and reflect on the data gathered in action (with the students in the studio) and in the final assessment amongst the researchers alone.

3.4 Reflecting

3.4.1 First Author's Positionality Statement. I acknowledge that my position as an educator and researcher in the field of digital jewellery carries power dynamics that can influence the research context. I selected the digital jewellery exemplars discussed in class as outstanding work and offered them to students as a source of inspiration, I structured the 10-weeks course plan and discussed the contribution of the co-authors as lecturers or workshop leaders. As an educator who follows a constructivist approach to learning, I see myself in the role of a facilitator to learners' creative journey as it unfolds through dialogue with materials, peers and tutors. I commit to creating space for discussion and reflection on what the students have learned, whilst I assist their development as reflective practitioners [68] and critical thinkers [13]. The assessment of their learning was through their final piece; the designs they produced; the students' own critique of their work, learning experience and reflections at key points in the course. The collaborative data generation, collection and analysis techniques implement a reflexive approach to thematic analysis and highlight my active role in knowledge production [11]: '[my] reflective and thoughtful engagement with [the] data and [the] reflexive and thoughtful engagement with the analytic process' [11, p. 594]. However, my work was not done in isolation: Throughout the study, I worked closely with my co-authors to

[4]The names of the students have been changed to preserve anonymity.

sense-check ideas and explore multiple assumptions and interpretations of the data. While I led the research, the data interpretation was collaborative.

3.4.2 ***Reflexive Thematic Analysis (RTA).*** RTA [11, 12] fits the context of this research as it allows us to analyse narratives in a manner that respects the subjectivity of the students' reflections while acknowledging and embracing the reflexive influence of the researcher's interpretations. The collaborative nature of the approach encouraged discussion among the research team to achieve rich interpretations of the data and to enable productive disagreements rather than attempting to achieve consensus of meaning. Themes evolved as the analysis progressed and we became more acquainted with the data [12, 73].

The data collection and analysis were carried out by the first and fourth authors. Adjustments to the plan made during the study were well documented in informal notes and in the first author's research journal kept over the course of the entire research. The first author used her journal as a tool for reflection in ongoing conversations with the fourth author; this, in turn, supported the interpretation of students' own narratives recorded in their annotated sketchbooks or expressed in class. As the project progressed, students' activities were monitored, and adjustments were made based on our interpretation of students' understanding. Our intention was to find balance between new content and students' understanding of electronics. As part of the assignment process, students had to submit their work and sketchbook for mid-term review; this was jointly assessed with the third author. Finally, the research team iteratively reflected on data and codes to generate, revise and reflect on themes. In the end, our dataset included mixed media from our own experience in the studio and the first author's observation notes and journal, the students' annotated sketchbooks and the examination of the students' pieces. By observing how students used the resources available (both theoretical and practical) we were able to see if and how what we prepared had been used or not used (that is equally important). By reading their sketchbooks we learned what elements were inspiring and why (Figure 1). By examining their digital jewellery pieces, we reinforced existing knowledge in the field or challenged it. Most importantly, how students appropriated and creatively expanded the poetic interpretation of electronics and interaction highlighted the unique contribution jewellers can make to HCI research.

During the whole process, we stayed open to the unexpected ways in which the students made use of and appropriated the resources we had created. We were then able to quickly respond to these challenges and reframe the activities (see Section 4). Our final step as researchers was to synthesise our reflection into new knowledge (see Sections 7 and 8) to open a design space for digital jewellery research.

4 Planning: Concepts and Circuitry

The process of designing and making the circuitry prototypes to be used in the class started two months before the start of term. The prototypes were designed to lower the threshold to enable jewellery students (that may as well be very sceptical of the value of electronics in their practice) to explore and use electronics. Our starting point and inspiration were blackboxes (see Section 2) and our goal was the ease-of-use of electronics. We were driven predominantly by design concepts such as 'Pointing North', 'Blowing Light' or 'Connecting People' (see Table 1); we also considered the size, costs and aesthetics of the electronics (i.e., E-Ink Screen). We attempted to use the same components in different prototypes to reduce complexity (i.e., Seeeduino XIAO board used in three prototypes and NeoPixel LEDs in five). However, at the implementation stage, we faced constraints that we had initially overlooked, namely: (in)compatibility between components from different providers, the needs to use different development environments for coding and the availability of online support (or the lack of it). To give an example, the board Seeeduino XIAO was chosen for its

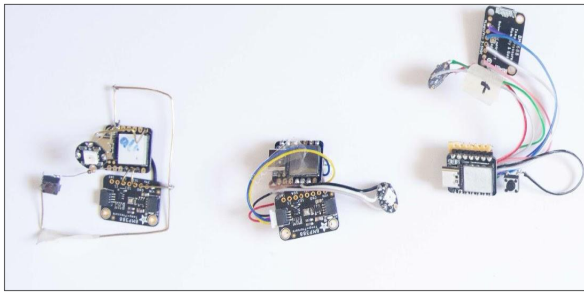


Fig. 2. The aesthetic potential of hardware for the *Temperature Prototype* (left to right): thick rigid wires, compact with wrapped wires and distributed with longer wires.

small size, affordability (£5 a board) and compatibility with the Arduino development environment, while the Circuit Playground Express board plus the Gizmo E-Ink was chosen for the aesthetic qualities of its E-Ink screen. On assembling the prototypes, we could not make the Gizmo E-Ink work with the Arduino environment, forcing us to use Circuit Python to program the E-Ink display. The result was an increased complexity as to implement the concepts we needed different boards and different programming environments.

The challenges we faced in implementing the concepts delayed the implementation phase. To complete the prototypes before the start of term we simplified some concepts. For example, as we could not make the GPS work with the intended board, the concept related to places was re-designed as the simpler clicking of a button instead of physically going to a place. Despite our efforts to speed up the implementation phase, we could not make a set of prototypes for each student. Thus we introduced two new concepts ('Pointing North' and 'Connected Brooches—proximity') for which students had to change the code using micro:bits. As later discussed in Section 6, the micro:bit coding session was fundamental to foster students' understanding of the key concept of input-processing-output and to stimulate experimentation with the dis-assembling and re-assembling of the proposed prototypes. The first and third authors were involved in the production of the prototypes to be used by the students. This resulted in different variations of the same blueprint as shown in Figure 2, which was an unexpected outcome. In a process of reflection-in-action [67, 68], we acknowledged the potential for different aesthetics created by flexible wires of different lengths or by solid metal wires. These variations of the hardware inspired us to include four variations of the software for 'Sensing Touch' with different triggers (short vs. long touch) and outputs (LED fading in and out or persistent light).

To summarise, the issues we encountered during the development of the digital prototypes forced changes that brought up a different approach to introducing jewellery students to physical computing than initially anticipated. We offered seven pre-assembled circuits in different hardware/software variations that were pre-programmed, and two circuits that students coded themselves using visual coding language and step-by-step instructions (see Table 1 above). As we became aware of the changes we were making in the resources, we adapted the way in which the resources would be used in the practice, staying open to its generative result.

5 Acting: The 10-Week Project

The project was part of the curriculum. It lasted 10 weeks, with two sessions each week for a total of 20 sessions (see Table 2). In the same period, students were expected to engage with design work in a self-directed manner. The students had no prior knowledge of physical computing, coding

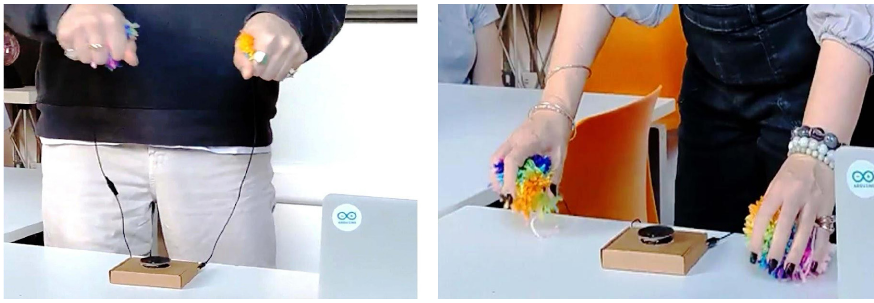


Fig. 3. The human body is more than a finger pressing a button. Students experience their body is conductive as each individual produces a different sound. (© PomPoms Project by Sam Topley https://www.samantha-topley.co.uk/projects.html.)

or electronics. Their final piece, as well as their annotated sketchbook and explorations, was an essential part of the assessment.

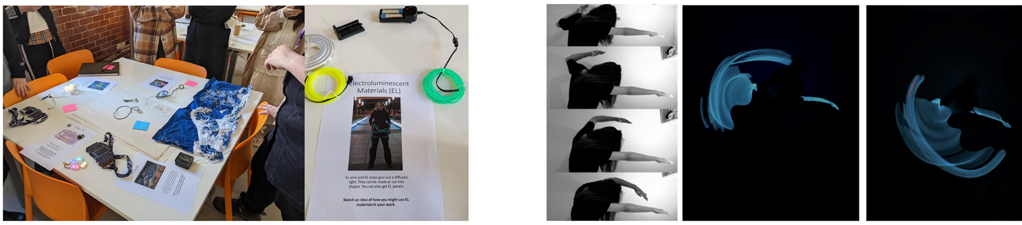
In the first week students explored what was personally meaningful to them using visual methods. In the following 5 weeks, theoretical lessons, practical lessons on physical computing, and show-and-tell sessions were interwoven with design crits to support students in thinking creatively and critically about the use of electronics as part of their jewellery practice. Students had technical support for advice and (limited) implementation. More in details:

- *Theory*: Lectures on Digital Jewellery, Interaction Design (week 2) and Critical Design (week 6) were delivered with a discussion of examples from research.
- *Physical Computing (Practical)*: Two sessions introduced computing and interactivity showing that the human body is conductive (Figure 3); students explored and discussed the interaction with the prototypes (Table 1); understanding what the code does with micro:bit (e.g., a different threshold value changes the behaviour of the prototype); demos and discussion of different sensors and interactions (i.e., tilt and shake).
- *Show and Tell*: Hybrid digital-material artefacts were presented and discussed with students, examples were a fabric intertwined with fairy lights that light up when touched or electroluminescent light wires. To better understand the relation between form, material and electronics (aesthetics and size), students were asked to design a form for the Selected Images prototype (Table 1).
- *Ways of Making (Workshops)*: Students were introduced to other materials than metal, a material they get to know well in the first year of their study, to expand their toolbox. They tried ceramics, cardboard making, screen printing, 3D printing and leather.

As part of the action research, we stayed open to the needs of students: we adapted, changed and rearranged the delivery of the content depending on the students' response.

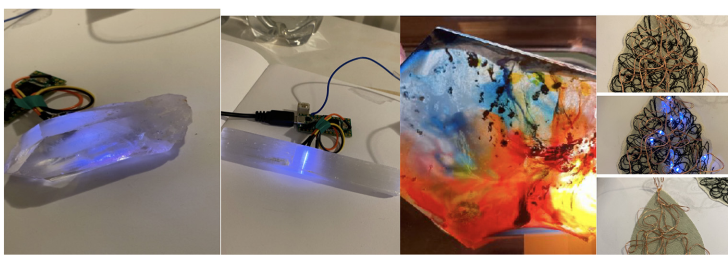
6 Observing: Annotated Sketchbooks and Final Pieces

Out of the 14 pieces created by the students, we discuss the 5 most representative of a creative use of the kit. The annotated sketchbooks of another three students are included in the discussion that follows in Section 7. These students were very engaged, they showed much independence and initiative, for example, exploring how a LED light changes when seen through different materials (Figure 5) or how metal, fabric or leather can complement electronics (Figures 6–9). Their sketchbooks detail their journey of exploration with some experiments becoming part of their final



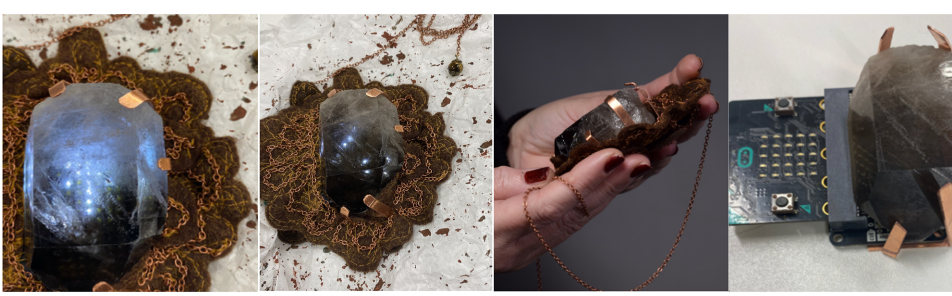
(a) (b) (c) (d)

Fig. 4. How show-and-tell inspired students: from left to right (a) a show-and-tell session in the studio; (b) how electronics (electroluminescent light wire) were presented in the session; and (c) a student's exploration of her swimming gestures displayed with the electroluminescent light wire (d).



(a) (b) (c)

Fig. 5. Explorations with light: from left to right (a) reflection and refraction with Clear Quartz Crystal, (b) Satin Spar Selenite; (c) UV resin and pigment as light diffusers; (d) experiment with fairy lights.



(a) (b) (c) (d)

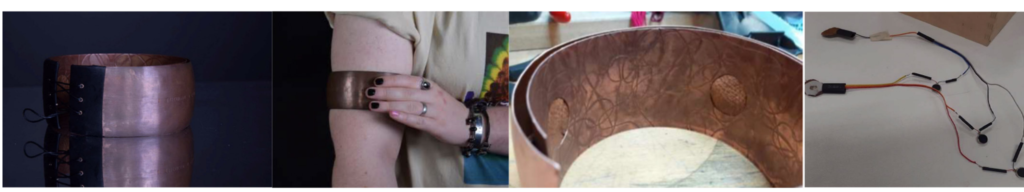
Fig. 6. *Take the Weather with You* is made of fabric, copper, crystal and electronics (scroll:bit LED, micro:bit, battery). The scroll:bit LED display is placed beneath the quartz crystal and set with copper shows an abstract representation of the sun (round with rays (a)) and snow (dots (b)). (a, b) The shape of the fabric and the embroidery are inspired by pinecones that fold their scales when it rains. (c) The copper chain to wear the piece as a necklace. (d) The making of the working prototype.

piece, such as the quartz refracting light (Figure 5, left), while others are abandoned, such as the swimming gestures displayed with the electroluminescent light wire (Figure 4, right).

An example of a student's progression is *Take the Weather with You* (Figure 6), a digital barometer that can be worn as a necklace. In the generation of her concept, Lesley was inspired by trying the 'Sensing Temperature' prototype. She used an Atmospheric Pressure/Temperature and Humidity sensor to 'predict' weather conditions that are then displayed on an LED matrix, attached to the micro:bit that displays her abstract visualisations of weather conditions (storm, rain, sun, thunder).

(a) (b) (c)

Fig. 7. Connected Brooches are a pair of connected digital brooches for two wearers. When the top layer of one brooch is spun, the other brooch lights up; initially low, the light increases in intensity as the spinning intensifies. From left to right: (a) Final form of the brooches in brass and fabric. The electronics assembles a potentiometer for each brooch, a microcontroller with WiFi connection, LED light and a LiPo battery. (b, c) Explorations of form and light: metal and fabric; metal, papier-mâché and human hair.



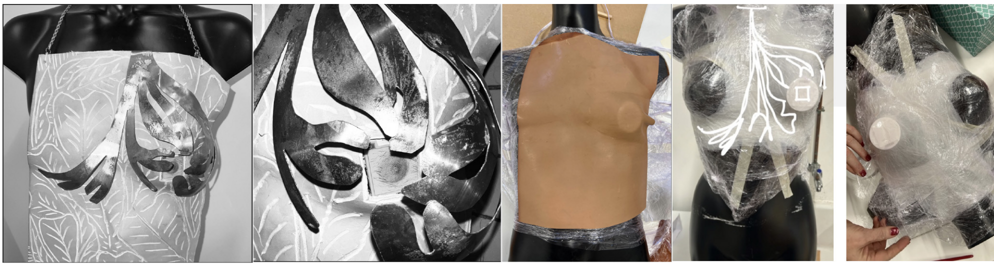
(a) (b) (c) (d)

Fig. 8. *Amulet for Anxiety* is a digital bracelet that vibrates when touched. A personal affirmation text is engraved on the outside (a). The piece is made of copper, leather and electronics (vibration motors, touch sensors, battery) (a, b). The circuitry is encased within two sheets of copper; holes in the inside of the metal sheet secure the vibrator motors, covered in leather (c). The vibration of the amulet is activated by pressing two touchpads (b, d) and could be fastened more tightly by pulling the strings (a).

In her final piece, Lesley fuses knowledge from lectures, show-and-tell and two practical sessions. By observing her progress, we saw the content delivered by us (how to trigger light output) was taken further by Lesley's individual initiative in the independent experiments she carried out on the refraction of light through different materials (Figure 5) that became central to her piece.

7 Reflecting: The Praxes of Jewellery Students Working with Electronics

We set out to explore what would make the jewellers' path into physical computing relevant to their practice. The motivation for our research was to facilitate the exploration and adoption of electronics in the making of meaningful, bespoke and crafted pieces of jewellery. Along the way we encountered challenges and difficulties, we changed our way and adapted to the circumstances, and, in the end, we were rewarded by the work of the students who shared this new route with us. In this section, we analyse how students' creative practices developed during the 10-week project using the Digital Jewellery Kit. We developed our understanding of the impact of the resources by reflecting on the students' annotated sketchbooks, their final artefacts and their participation and discussion in the studio. Through an organic RTA process of reading, reflection and discussion among the team members, similarities emerged across students' work showing the recurrence of certain elements (e.g. similar reflection on their new understanding of computing or how their craft skills applied to the making of their final piece). It then became clear that jewellers working with electronics in a hands-on approach extended their practices by finding value in interaction



(a) (b) (c) (d)

Fig. 9. Reverse Gender Breastplate combines male and female chest features: the lower part in engraved leather is male and supports a feminine half-breast piece made of gilding metal (a). Through the female breast piece, in the close-up (b), we see the E-Ink screen encased within the leather of the male torso; it displays a male nipple. The E-Ink Screen is mounted on a Circuit Playground Express. (c) The design development of the male torso in leather and (d) the shaping of the female half-breast.

design; embracing the digital besides the physical; and making meaningful and crafted pieces of digital jewellery. Each of these elements is discussed in turn.

7.1 Finding Meaning in Interaction Design for Jewellers

7.1.1 The Value of a Hands-on Engagement with Digital Interactions. Students approached digital jewellery with no awareness of what interaction design is and had to overcome an initial strong aversion to the whole topic as they could not see how that was in any way relevant to them, their study and their practice. The theoretical lectures on interaction design and digital jewellery delivered in week 2 provided the students with an understanding of digital jewellery practices through the analysis of others' work. We started to see students' interest rising with the introduction of the kit (Table 1) explained during the physical computing sessions. The more the students experimented and explored the digital interactions themselves, the more engaged and engrossed they became. With the 'Sensing Touch' prototype, they noticed that when a pair of scissors touched the sensor that the LED was constantly on, and that the LED would light up when a person (a body) was close to the electronics but with no direct contact with the sensor. Students then questioned what would happen with a piece of jewellery made out of metal or what was the meaning of touch or presence. This discussion brought their attention to the role of the body in the interaction which is key in the jewellery practice. A more inquisitive mind frame was formed pushing the students to think of the many ways in which the wearer can interact with the piece and how a poetic relationship is formed. The PomPoms activity (Figure 3) helped students to grasp in practice that human bodies conduct electricity in different ways as different sound outputs were triggered each time a different person interacted with the PomPoms. Their journal showed how they discovered the uniqueness and playfulness of the interaction: 'The input [temperature sensor] could be to hold in the warmth of the hands, or it could be detecting the temperature outside or it could be breathing when the piece is blown' (Lesley), 'This one is particularly interesting to me because although it only has one sensor, the input could be multiple things, it could be [ambient] temperature or it could be breath'. (Laura), 'Temperature input could be altered by locations, seasons, stress, illness, breath, talking, touch'. (Keith). Interacting with the physical prototypes gave the students more time to reflect and critique the technology they were handling; for example, the 'Selected Images' prototype, which can only hold three images, made students discuss 'the preciousness of the three images' and how these three could be more meaningful than the multitude of images in a mobile phone. They commented on the persistence of the image on the E-Ink screen after the battery dies or when the device can no longer be updated. These comments showed some degree of critical thinking. With the 'Pointing North' and 'Connected Brooches (Bluetooth)' (Table 1) the students explored abstract concepts, 'giving direction—maybe to one's life during a difficult time', and 'emotional proximity to a loved one', respectively.

7.1.2 Active Engagement with a Piece Is More Meaningful in the Context of Digital Jewellery. After the two physical computing sessions, jewellery students started seeing the potential of electronics within their practices and discussing meaningful applications based on the sensors at hand. The role of the body and the meaning of the interaction were also extensively discussed. In making the pair of communicating brooches (Figure 7), Louisa shifted the interaction proposed by the prototype 'Connected Brooches (switch)' to fit with the jewellery ethos: 'I think that touching the device in order to get an output is more poetic rather than pushing a button because it feels like you are doing it rather than the button'. When a brooch is spun by the wearer a light begins to glow on the other brooch increasing in intensity as the spinning intensifies: 'this is a more poetic interaction as the wearer can feel as they are really making that interaction happen. It is active interaction and presents thoughts of the other person'. Similarly, in making a digital amulet that vibrates (Figure 8) Alice reflected on her design decision to choose a touch sensor instead of a pulse sensor '[because] your heart rate doesn't always go up when you feel stressed or anxious, so I wanted to make it work for every occasion so having it touch sensitive made it more accessible'. Their rationale suggests that an active engagement with a piece is more meaningful in the context of digital jewellery.

7.2 Embracing the Digital besides the Physical

7.2.1 Expanding Jeweller's Material Palette: Understanding Electronics as Material for Jewellery Design. Students were introduced to physical computing concepts in a fluid and organic way through hands-on sessions, show-and-tell and group discussions. Taken as a whole, the activities presented three key elements of physical computing: *interaction*—what happen when the human body, another object or the environment engages with a prototype; *hardware*—sensors, actuators, boards and wires of different shapes and sizes; and *software*—what code is for and what happens when it is changed, e.g. different values for a threshold result in different behaviour.

Some activities emphasised one element more than others. For example, the hands-on with the prototypes showed a range of hardware inputs (sensing touch, light or temperature) bringing the students' attention to the interaction while the show-and-tell with electronic components widened their awareness of what is technically possible: 'This session gave me an understanding of what technology is available to me for example conductive charging, using temperature, heart rate, location, movement or buttons to get an output'. (Sam). Similarly, the micro:bit prototypes (Table 1) focused on software and coding rather than interaction and hardware. 'This threshold is how much of something is touching it, meaning the more metal is touching the sensor the lower the threshold needs to be in order for the sensor to be activated by human touch'. (Keith commenting on a pair of scissors or a human body closing a circuit). Students were not intimidated by the visual language of micro:bit and were pleasantly surprised when they discovered they could 'code' using instruction-blocks and explored different interactions with the board; they found it accessible and engaging and the coding session essential to understand what is behind the digital components and how they could manipulate software themselves to create different digital interactions. A variety of provocative examples from digital jewellery as well as from the DIY movement were presented and commented upon from opposing perspectives. These provocations helped them to step outside the technology frame of mind of what is feasible and push students toward thinking how they could use electronics in their practice. The following comments refer to the interaction with PomPoms (Figure 2) where the human closes the circuit and the sound emitted varies from person to person as different bodies conduct electricity in different ways: 'our bodies completed the circuit' (Carl) and 'What I found interesting about this activity though was how the sound differed when held by different people, showing everybody reacts and shares electricity in different ways'. (Laura). By the end of the physical computing session, students with no previous experience or any understanding of physical computing had grasped the basics of input-process-output, sensors and actuators connected, the variety of electronics they could use and how interchangeable they are, e.g. the input from different sensors can have the same output. Each session served a different learning purpose: the prototypes introduced them to the logic of interaction design and to develop an awareness of how hardware and software communicate; using the micro:bit showed how their code changed the interaction and impacted their design, which they found intriguing; the show-and-tell was provocative and inspirational to understand how they could combine their existing material practices with electronics.

7.2.2 Looking at Electronics through a Jeweller's Lens: Combining Physical and Digital Aesthetics. Electronics have a physical presence, form and aesthetics that can drive the design process or clash with the designer's vision. The examples from the makers' community (shared as part of a lecture), the show-and-tell and the prototypes with the short or long wires and the thick metal wires as connectors (Figure 2) opened students' imagination and instigated insightful conversations about the aesthetic values of electronics, if and how that aesthetics and materiality should shape the pieces and, thus, become part of a jeweller's toolbox. Students discussed the placement of the electronics, whether it should be concealed within the piece (in a brooch) or behind the body and out of sight (on the back hanging from the neck) or, instead, be shown as a feature: 'I became more aware of the size and shape of the electronic pieces we were shown and the way the wires and circuit are completed. Wires can be bent and free form around the chip, or, alternatively the wires can be coated in plastic and hidden behind the chip'. (Laura); '[...] thinking about the potential of using thick copper wire and incorporating these essential wires into my design, hiding them in plain sight and distracting away from the digital components purpose'. (Alice); and '[...] the electronic wires can even be sandwiched or embedded within materials such as metals or ceramics' (Lesley).

As students progressed in their experimentation with the materiality of electronics, new and unexpected aesthetics emerged from their craft practice that changed the way in which the input and output is perceived. Figure 5 aggregates the work of three students who explored how to 'display' light other than from the LED directly: Lesley explored how different crystals reflect and refract the light in different ways (Figure 5, left); Amber created a visual impression of the sky using UV resin and pigments to diffuse the light coming through (Figure 5, centre); Jane brought in fairy lights to be fused into their piece (Figure 5, right and the final piece is the *Time Capsule* in Figure 10). With their experiments these students extended the kit offering new digital-material hybrids that could inspire others.

The analysis of these pieces shows that jewellery students explored the aesthetics of their artefacts through a combination of materials that they were already familiar with (metal and gemstones) and other materials new to them, namely leather, ceramic, wood and electronics. In doing so, they started developing a new visual language specific to jewellery as in the aesthetics of electronics with solid wires and the board exposed, or the materiality of light. A key question for them was to decide if and how the aesthetics of electronics should guide the aesthetics of their piece. Even though in their exploration and group discussion students expressed an interest in revealing the aesthetics of electronics, in their final design they all discreetly encased the hardware. This may be due to a lack of confidence in combining electronics and traditional materials in aesthetically pleasing ways, or to the fact that more traditional aesthetics of jewellery overruled the aesthetic of

(a) (b) (c) (d)

Fig. 10. Time capsule is a hand-held piece of digital jewellery that connects a mother with her three daughters. Each daughter is represented by their star constellation. The light constellations light up independently when the wearer tilts the piece in her hand in three different positions, one for each child (a). The piece is made of electroformed fimo and electronics (micro:bit, fairy lights and a battery). (b) The final piece after electroforming process, (c) the piece upside-down shows the drills with the marking of the constellations and (d) the making of the circuit.

the digital components. Yet, we may expect that, as their knowledge and confidence grow, jewellers may decide to celebrate the aesthetics of electronics or to combine digital and material aesthetics more tightly.

Unexpectedly, jewellers working with electronics added value to the aesthetics of the electronics itself, as in the experiments with LEDs and fairy lights (Figure 5, right; Figure 10, right). Jewellers can creatively work with electronics in a very open and explorative way that is rooted in craft knowledge and material practices. In doing so they extended the expressivity of electronics, and the new knowledge acquired gave them the confidence to use circuitry that fit their design. In turn, their experiments can become part of the kit to be an inspiration for others or new projects.

7.3 The Making of Meaningful and Crafted Digital Jewellery: The Values that Drove the Creative Process

7.3.1 Reflecting on the Use of the Digital Jewellery Kit for the Design Development of the Final Pieces. To ease the entry of jewellers into the world of physical computing we created the Digital Jewellery Kit with circuitry prototypical of interactions (Table 1) inspired by research in digital jewellery therefore more likely to engage the students. The circuitry encouraged students to ideate and think of meaningful contexts for digital jewellery. Initially, we envisaged the different resources within the kit to be used as blackboxes, closed and ready to use. We expected students to develop a concept around one specific circuitry and add value to it via material exploration and interaction with the body. All but one student ignored the prototypes and used elements of the kit that fit their design ideas. We observed that the more refined and complete the concepts were, the less likely students would choose a prototype. Elementary functionalities such as touch, tilt or temperature stimulated students' creativity much more than 'the complete thing'. This path was opened by the use of micro:bit, a board we initially ignored as we intended to avoid coding. Using micro:bit the students became aware of how to manipulate the digital by modifying the circuitry in a process of 'dis-assembling' and 're-assembling' old elements with new ones to implement their own concept. For example, Alice in her *Amulet for Anxiety* started from Sensing Touch but changed the output to be vibration motors. Moreover, the concept did not need a microcontroller to work as it was a simple sensor-actuator pairing thus reducing complexity. In essence, we observed that, the more students took ownership of their ideas, the more excited they were to explore components that fit their purposes rather than reusing what was offered to them.

To summarise, the digital kit showed meaningful examples and helped students understand basic logic in programming. A turning point was the use of micro:bit to learn the basics of computing. The more we unpacked the 'blackbox' of electronics and gave away the power to change the functionalities (coding), the more creative students became and owned their ideas. However, technical support was required for them to achieve their aspirations. It should be noted that not everyone engaged with the toolkit and one student proposed a concept that was far beyond the purpose of the project and the technical support available. The student envisaged the use of an app paired with a digital jewellery. In summary, we witnessed how the knowledge and expertise of the technician scaffolded the confidence of the students pushing them to believe they could implement what they had in mind. However, students that did not build on the toolkit's interactions could not prototype their ideas within the duration of the project.

7.3.2 A Continuous Dialogue between Their Exploration of Technology and What Is Technically Feasible. During the 10 weeks we observed students' conceptual understanding develop. Each student had their own personal growth resulting in very different artefacts that represented their individual values. Their initial uncertain attempts to form a concept became meaningful as time passed and more knowledge was gained, even though their technical understanding of electronics and programming remained limited. Their awareness of 'dis-assembling' and 're-assembling' enabled the students to create their own concept by altering the prototypes proposed that, from inspirational, became building blocks.

We saw that the values driving their design and development are their vision, the way in which they translate affection and emotion into interaction. However, this evolution and change is in their design is in continuous dialogue with their exploration of technology and what is technically feasible. In *Connected Brooches*, Lydia would have not used the spinning mechanism in her project if the idea to change the intensity of the light on the other brooch to show the intensity of thinking was not part of her design. At the same time, it was the *Connected Brooches* with the light fading in and out that inspired her to go beyond the light switch and to show intensity and lasting of thought and affection as an integral part of her piece. Similarly, *Amulet for Anxiety* shows a continuous dialogue between the material and the digital where one reinforces the other: The leather amplifies the vibration on the skin as it does the manual tightening of the bangle. We argue that in these two examples the digital exploration changed the making practices and guided the design process. In return the creative practice created new meanings, more intense and prolonged interactions, that could expand the poetic vocabulary available to the creatives.

In other cases, we saw the materials changing the digital. In the *Take the Weather with You*, how the crystals diffused and refracted an LED light changed the form of the functionality of the light. Louise's material exploration with LEDs and different crystals were catalysts in this expression and a result of their craft practice. In traditional jewellery practices, much of a gemstone's perceived beauty lies in the performance of how light reflects and refracts throughout the stone. What we call the 'sparkle' of a gemstone in traditional jewellery, in digital jewellery could be understood as the visual effects of light that are unique and visually pleasing. Lesley's experiments with light and material were unique, *Time Capsule* (Jane) too derives from experiments with light and extends the possible light emitter to fairy lights to produce an effect that is qualitatively different from LED light. Another example of transforming light is the coloured sky in Figure 5, centre. These practices on how the lights from a digital source diffuse, reflect and refract when filtered by a material can become a new LED+material building block in the toolbox of the jewellery makers. We believe this is only the first example on how creative practice can change and expand physical computing.

7.3.3 The Physicality of the Body Gives Meaning to the Digital. Students explored how the physicality of the body gives meaning to the digital, for example, how the temperature sensor during the physical computing sessions could be triggered by rubbing, breathing or the warmth created by the hands, creating in this way, longer and more intimate interactions. This deep knowledge surfaced in their final pieces. In the *Connected Brooches* project Louisa used 'spinning' (rather than button pressing) to extend the interaction and to represent the active engagement that communicates thinking of the other person. In *Amulet for Anxiety,* Alice substituted LEDs in the Sensing Touch Prototype for vibration motors in her armlet to control anxiety; the manual tightening of the leather straps magnifies the sensation of pressure produced by the motor. This piece is the result of a careful thinking on how the materials (metal and leather), the human interaction (tightening the armlet) and the digital (the activated motors) are designed together to amplify the meaning and effect of the piece. In *Time Capsule* (Jane) the piece fits her palm, and the movements of her hand (captured by a tilt sensor) activate a personally meaningful light display, one of the three constellations (implemented with fairy lights) that represent her children. Carl's *Reverse Gender Breastplate* is a critical stand on the physicality of the body in relation to gender and used the E-Ink screen (that displays a nipple) to open a discussion on gender fluidity. The male nipple-screen nested in the female metal breastplate is a rare example of exposing rather than concealing the technology. Such a variety of examples illustrates that in the jewellers' practices the body is explored in open-ended and experiential ways and, in so doing, it adds a deeper meaning to the digital. The *Reverse Gender Breastplate*, for example, moves away from the traditional digital jewellery artefacts found in the literature. It demonstrates how jewellers can widen the conversation around the role of technology in gender, and identity and convey an understanding of the body that goes beyond biometric data and touches on creativity and critical thinking.

8 Discussion

Material-centred disciplines such as design, craft and art practices have expanded and advanced HCI with new ways of working with materials and their experiential qualities that complement and enrich established computing and interaction. This research adds to the conversation from the perspective of jewellers who initially approached computation with scepticism and then grew their interest through hands-on exploration of a series of pre-assembled circuits alongside inspirational examples that supported their development of how the physical (wood, leather, fabric, metal, ceramics, etc.) and the digital (electronics and coding) could be combined in meaningful ways to advance their existing practices.

In the next section, we discuss the physical-digital material practices and contextualise our findings within the broader literature. We discuss how jewellery students approached this new material before we present four takeaways that can be used to develop toolkits for creatives in the future.

8.1 Physical-Digital Material Practices within Jewellery Practice

Within interaction design, Wiberg et al. [83] presented the notion of material assemblages to conceptualise the physical and digital material integrations and offer a multifaceted view on material integrations. Such practices focus on blending the physical and the digital [41] and on how the digital can be further integrated with our physical and social world [45, 59]. Our research focused on the latter. We explored how jewellery students could embrace the digital material in their practices, and in so doing bring their own perspective in combining the physical and the digital. Practices such as hybrid craft [34] that handcrafts circuitry with different materials [14, 69] or hybrid crafting [76] that combines silversmithing with electronics integrate material and digital at the functional level (e.g. sensing). The toolkit we designed goes beyond craft+computing to include critical making [64], a practice that highlights the interwoven material and conceptual work that making involves. From this perspective, the jeweller's practice aligns with Giaccardi and Karana's work on material experiences [33] as it goes beyond the potential of the materials as functional to cover aesthetic considerations and the social and cultural contexts of those designs. We argue that jewellers' material practices entangle the practical/functional to the social and cultural aspects of interaction and the aesthetics of the pieces they create. By embracing the digital as a new material, jewellers open a design space where they can discuss the meaning and significance of digital technology and develop their identity as makers in the digital space through the design of new examples of digital jewellery.

Drawing on Schoemann and Nitsche [66], it is important to introduce jewellers to digital technology as a new practice in an exploratory and experimental way. We saw that not all the students engaged with electronics in ways that enhanced their existing practices. For those who chose to push the boundaries of their making, the resources and toolkit enriched their embodied knowledge via a practical and theoretical understanding of the digital as a new material. They then unpacked this new material and created their original applications using simple interactions that show personal expression. As their understanding developed over time, we saw students moving away from the dualism of physical-digital and getting closer to what Devendorf refers to as 'physical-digital coproductions' [24] that draw attention to the tension within physical-digital and put emphasis on the mutual construction of human and non-human (technology). Students' final designs are not encasings for electronics; they are physical-digital co-productions that demonstrate their craft skills and their ability to design interactive artefacts that can be meaningful to their practices.

8.2 Four Takeaways for Future Development of a Digital Kit for Jewellers

8.2.1 Theory and Practice Need to Be Balanced. We acknowledge the value of theory, design examples and provocations alongside practical hands-on explorations with electronics to encourage students to be critical and to develop meaningful contexts for electronics. We believe that a synergy between theory and practice is crucial, and jewellers should be exposed to conflicting ideas and different opportunities. This approach to toolkit design that brings together theory and practice is new across creative disciplines (including wearables and e-textiles) as current toolkits focus on easing the use of electronics overlooking the strong link existing between theory and practice. Our future development of the Digital Jewellery Kit could include provocative examples of: (i) the aesthetics of electronics vs. the aesthetics of jewellery and the interplay between the two (drawing on similar work done on e-textiles); (ii) jewellery-specific interactions; (iii) limited content vs. infinite files. The provocations should be part of a studio discussion around examples from interaction design, digital jewellery, critical and speculative design that offer meaningful applications of technology.

In this research, to support the project, we introduced the poetic dictionary for personal engagement with the digital as a theoretical framework for design [47] which was valuable in analysing design examples during the theory sessions. More research, however, is needed to explore how the use of this framework may inform students' concept and design development as their project progresses.

Alongside using an existing theoretical underpinning, we stayed open to explore how practice can inform theory. A key takeaway in developing future digital jewellery practices is the consideration of how the body gives meaning to the digital through active engagement (i.e. rubbing, blowing, holding, wearing) or through its physicality (i.e. the warmth of the hands, breathing). From the physical computing sessions to the final pieces, it was clear that jewellery students brought a strong focus on the role of the body in the interaction—from controlling the intensity of the light source through spinning a component of the jewellery piece to physically pulling to tighten the bangle and amplify the vibrations—thus the interaction with the piece. Research into digital jewellery from an HCI perspective sees the body as a location for the digital devices [42] and familiar interactions with jewellery (i.e. changing a ring on the fingers, or spinning the ring on a surface) are explored as input modalities [5, 20]. Our findings strengthen the importance of considering the experiential qualities of the body as input for interaction as discussed in previous research into digital jewellery [48].

8.2.2 Combining Electronics with Subject-Specific Materials and Interactions: A Hands-on Approach. We saw that students extended the expressivity of electronics, and the new knowledge acquired gave them the confidence to use circuitry that fit their design. Indeed, the most creative projects created a dialogue between technology and materials such as metal, leather, fabric and quartz, a key and novel contribution to the digital jewellery practice. A further consideration in planning digital tools for creatives refers to the combination of electronics with the specific material of the craft. In e-textiles, there has been a wide exploration of combining digital with materials such as conductive fabrics and threads to create handcrafting textile interfaces [60–62]. In jewellery, a first step in this direction has been taken by Tsaknaki et al. [76] who explored how electronics and silversmithing practices can be combined at the basic level of creating buttons, sensors and actuators using traditional craft techniques with metal. In our explorative study, we saw how jewellers worked with LEDs+material to handcraft jewellery interfaces. In some cases (*Connected Brooches* and *Amulet for Anxiety*) the digital exploration changed the making practice and in other cases (*Take the Weather with You* and *Time Capsule*) we saw the materials changing the digital (see Section 7.3). We believe this is only the beginning of how creative practice can affect and expand physical computing. Such practices can be a positive addition to digital jewellery making as they may reinforce the message that digital belongs to jewellery. We anticipate, in following the e-textiles path [43, 44], to see a wider exploration when combining digital with materials unique to jewellery practice such as metal and gemstones or more contemporary materials such as ceramics, textiles or found objects to create handcrafted jewellery interfaces. These experiments can become part of the digital jewellery kit to be an inspiration for others or new projects.

In line with the research by Zhang et al. on introducing an electronic toolkit to textile designers [84], our toolkit and resources also supported rapid hands-on tests and experiments between physical design and electronics, appealing to jewellery designers' tacit nature. Our findings strengthen the higher value of demonstrating the affordances and general principles of technical functions rather than explaining circuitry and programming mechanisms in detail [84]. The resources we provided mostly skipped the learning of electronics favouring instead spending time to help students investigate how to better embed interactive qualities into their jewellery. However, during this process, we found that understanding some basics of electronics and programming simultaneously prompted jewellery students to conceptualise computers not as a blackbox, but just as another design material operating in concert with other physical materials. Jewellers have an interest in materials and their tactility, and we argue that the physicality, aesthetics and tactility of the digital fits within their existing material practices, allowing them to experience the digital material and its qualities in similar ways that they would experience a physical material—with their hands, in tactile ways.

8.2.3 The Digital Toolkit Should Be 'Dis-Assemble-Able'. Our aim to lower the bar for jewellers to enter physical computing pushed us to implement blackboxing physical computing to reduce complexity [9]; however, this strategy proved not the best in the creative domain. Our findings show that it is crucial to empower creatives to unpack the given prototypes in a process of dis-assembling the components to re-assemble them differently to implement their unique concept. While existing off-the-shelf technology such us PomPoms and the pre-assembled circuity and their variations were important to show examples and acted as starters for conversation of potential applications, it is in the dis-assemble-re-assemble process that creatives take ownership of their digital design.

We, therefore, propose the term 'digital assemblages' to describe prototypical concepts created to inspire while, at the same time, being reconfigurable to implement other concepts. Conversely from a kit of hardware and software with specific interactions to be assembled by users [31] or widely available toolkits (i.e., Arduino) that require an understanding of electronics and coding from the beginning, in our process we assembled several prototypes and let the creatives dis-assemble and reconfigure the components with new meanings that expanded their material practices. In so doing, we contribute to the DIY technology for creatives with a new concept of toolkit that sits somewhere in between constructive assemblies [50], modular kits, toolkits and examples [14, 71], and the concept of un-tool-kit [52] (Section 2.1 discusses the different toolkit types). Our approach allows jewellers to appropriate electronics functions directly within their own designs, for example, the closing of the brooch pin when wearing it closes the circuit and starts the interaction, or the conductivity of a metal bangle can add as a switch when it is put on the wrist in touch with the skin (that is conductive too).

In summary, we argue that the process of dis-assembling and re-assembling elements that were initially introduced with the pre-assembled circuity proved to be crucial in unleashing students' creative potential in using the digital in ways more in line with their practice.

8.2.4 Some Level of Coding (Possibly Block/Visual Coding) and Technical Support Is Required for High-Ceiling Applications. Our results show that the maker's confidence gradually improved as their technical knowledge expanded and their skills grew thanks to the technical knowledge and skills available to them in support of the implementation of their concepts. To enable jewellery students to explore electronics, the technical support included 'coding' and assembling the final piece, the type of technical support not needed with blackbox toolkits [9, 16]. Our observations suggest jewellers need enough structure to understand the key elements of computing, and then quickly prototype their own ideas without restricting the variety of digital interactions they create. In essence, jewellers need resources that enable both easy assembly of electronics and full agency in the design process.

A key point in the making of the pre-assembled circuitry is to limit the complexity required to use them. We experienced in practice that the micro:bit, with its a large range of in-built hardware programmable with visual blocks, gave students agency in their creative process. We offered examples that students could code themselves using visual coding language and step-by-step instructions. This process is similar to examples provided by DIY communities (such as the one that has grown around Arduino) with the unique addition that the concepts have meaningful applications within the jewellery context. In summary, the micro:bit examples moved the students away from a blackbox thinking as the circuitry encouraged them to ideate and think of meaningful contexts for the interactions micro:bit offered (e.g., *Facing North, Connected Brooches*). This approach moved students towards physical computing and being experimental while the technical support supported them to move from the experimental phase to the realisation of their own ideas. Similar to a traditional jewellery technician who helps students in making jewellery using traditional techniques such as stone setting or soldering, a digital technician with a sensitivity towards craft can offer vital support on physical computing and the making of physical prototypes that are in line with the creative's craft. In summary, we suggest that working with the limitations of the toolkit and offering technical support for hardware and software within the constraints of the craft is important in introducing jewellers, and creatives more in general, to physical computing. An additional recommendation is for technicians to use components that they have used before, they are familiar with and confident they can help students to complete a prototype in a short period of time.

Our recommended approach sits somewhere in between designing resources for autonomous making vs. making with technical support. As this was the first time the jewellery students had worked with electronics and computing, technical support was vital to guide their explorations. We experienced that the knowledge and expertise of the technician pushed the confidence of the students that they could implement what they had in mind. Further research is needed, however, to find the optimal level of physical computing that empowers jewellers to engage with creative applications of the digital material whilst keeping the entry bar low to allow implementation with limited technical support.

8.3 Towards Contemporary Hybrid Craft

The participation of BA students in this research, rather than established jewellery designers, could be considered a limitation. Instead, we believe that the continuous 10-week engagement with students, which might be extremely difficult to implement with professional jewellery designers, enabled us to fully unpack our practice and to revealed critical points in the field of hybrid craft, an area of growing interest in HCI.

Two positions emerge from the HCI literature. The most shared sees computing as a practice where electronic components and circuits are the materials of digital craft [15, 52, 60]: Here computing is merged with other craft practices to create a new, explicitly hybrid craft-computing practice. Examples stemming from this position are fibre arts [56], papercraft [69] and silversmithing [76]. Only a minority of authors share the second position that maintains the two practices, craft and computing, as distinct [22, 82] arguing that the embodied knowledge of craft practitioners in working with materials and their holistic engagement with the making processes is often missing in the first approach. In this perspective, craft goes beyond the use of specific materials to include the embodied skills of 'thinking through the hands' [35, 40]. The craft theorist Dormer [63] states that '[i]t is not craft as "handcraft" that defines contemporary craftsmanship: it is craft as knowledge that empowers a maker to take charge of technology'. An example of this approach is the work of Tsaknaki and Vallgårda (2023) who see craft as a matter of care when designing computational things [75]. Exploiting the conductive property of metal, typical of jewellery, and combining it with non-conductive materials such as wood, Tsaknaki et al. create small 3D sensors made to be worn as jewellery, close to the skin and activated by different types of hand touch. In her work [74, 76] we see how the deep knowledge of the jeweller she collaborated with, in combination with the researcher's awareness of the basics of computing, enables her to create new materialities imbibed with the aesthetics of jewellery to perform sensory rich tangible interactions. Rather than a juxtaposition of the two practices, as in the first positioning, here it is the craft that reframes the computational components within the values of the craft itself.

In jewellery, key values are the aesthetics, the closeness to the body, the symbolic meaning and the affective interaction. These same values are reflected in the digital jewellery pieces created by the students made with care in both the selection of materials and electronics and the maker's investment in translating affection and emotions into interaction (see Figures 6–10). We see the making of digital jewellery as a matter of care and focus expressed through the *development of empathy*—the ability to understand and interpret the needs and desires of the wearer and the *acquisition of digital and material skills*—the ability to make, including a deep understanding of different materials, their properties and manufacturing processes. We see digital jewellery education as the balance between developing empathy and acquiring skills, although there is very little evidence of jewellery students being exposed to digital technology besides the use of 3D manufacturing. A study in Denmark [2, 3] showed that engaging with wearables research can be hugely beneficial for the new generation of jewellers who become exposed to new forms of empathy mediated by technology. However, their institution's educational program focussed on developing empathy to generate concepts: The making was entirely delegated to others (interaction design students and technical experts). Conversely, we built on the praxis at Sheffield Hallam University in the UK, centred on studio-based jewellery education that values the acquisition of new skills and the hands-on engagement with materials through tactility and experimentation. As described in detail in this article, in our approach we do not delegate the technical implementation to experts, as done in the Danish study, but introduce students to micro-electronics and digital technology as part of their skill development for their future craft. We see this as a first example of teaching contemporary hybrid craft with an emphasis on skills and making as an approach to handling the digital and manipulating its interactive capabilities. Specifically, the students involved in this research were in their second year, had acquired the foundation of the craft the previous year and were expanding their jewellery skills towards new materials and new processes. Therefore, the introduction of digital technology at this stage fits well with the learning program and the extended 10-week course is a unique example of what could be achieved as part of a structured contemporary hybrid craft education.

This approach to teaching hybrid craft as an integrated discipline is different from the way technology is introduced to fashion students as a new material to explore [46, 84]. Teaching jewellery students about electronics is still in its infancy, but so is teaching computing students material-based approaches to physical computing as computer labs are not equipped with handcraft workshops [18]. Tailored methods for teaching physical computing can greatly benefit different craft practices and the field of hybrid craft overall. Here we contribute to the discussions on experiential approaches to teaching physical computing as part of craft pedagogies, and thus getting closer to what some refer to as Digital Bauhaus [26], the attempt to harmonise science and technology advancements with art and humanities sensitivities.

8.4 Inviting the HCI Community to Collaborate with Jewellery Practitioners

Even though there is an extensive community of HCI researchers who work in the field of crafts [29, 57, 74], there is limited research available on the material practices of jewellers working in this space. However, our study shows how jewellers bring sensitivities, care and emotions to the design of interactive experiences from which HCI practitioners can learn, particularly if they are designing wearables.

Jewellers use materials and forms specific to their practices that are very different from those common in HCI. The students' work in Figures 6–10 is very expressive and has sensual properties that technology-led wearables have not. Through a complex and rich entanglement of different elements, digital jewellery holds certain qualities that provoke interest and admiration, that invite touch and interaction and evoke feelings and memories. Achieving this is not straightforward: A closer collaboration with digital jewellers can offer HCI researchers opportunities to learn how these qualities and acknowledge the value of experimentation as a way to discover more expressive forms.

Jewellers' experiential process of making brings their material and emotional sensitivity to digital interactions [25]. Our research showed that continuous dialogue between digital and physical materials creates opportunities for more meaningful, engaging and deeper interactions. The manual tightening of the bangle on Amulet for Anxiety (Figure 8) amplifies the vibration on the skin while the spinning mechanism of Connected Brooches (Figure 8), which controls the intensity of the light on the other brooch, links the lasting of thought and connection in the relationship between the two people wearing the brooches. The final pieces are the output of *physical-digital co-productions* (following Devendorf and Rosner [24]) that emphasise the dynamic relationship between digital and physical in a continuous process that shapes and questions the tensions between the two opposite physical-digital [24].

Jewellers have an understanding of the human body that goes beyond biometric data and touches upon creativity and critical thinking. The physicality of the body can give meaning to digital interactions both as a trigger for expressive interactions through acts of rubbing, breathing, wearing or holding, and from a critical standpoint concerning issues of gender and identity. The proximity of digital jewellery to the body fosters intimacy that is expressed through specific gestures (pulling the strings in the amulet or spinning the brooch) or provocative layers of interpretations (*Reverse Gender Breastplate*, Figure 9). HCI practitioners could learn the power of such symbolic interaction to overcome the currently pervasive literal representation of the body in wearable design.

In return, HCI practitioners can support jewellers in exploring how to make the digital more tangible and easier to manipulate. Jewellers are interested in materials and their tactility and digital interaction can fit within their existing material practices. When a material and the tools to handle it can be associated with a direct manual encounter, the maker becomes a crafter [57]. However, as we have shown in this study, for digital functions to be meaningful to jewellers, they must acquire some level of understanding of it. Building on our work, HCI practitioners can create digital assemblages evocative of meaningful functionalities that empower jewellers to de-assemble and re-assemble electronics in new ways to become crafters of digital interactions. The blackbox technology, then, is opened up to offer new creative purposes to be explored and materialised [38].

9 Conclusions

In this article, we presented the design development of a digital jewellery kit used in a 10-week project in which second-year BA jewellery students had to design a digital jewellery piece. We wanted our kit not to limit creativity, but to invite a wide and bold exploration of electronics and their applications concerning the wearer. We started proposing a set of digital prototypes that we pre-assembled to be used by the students 'as is' while their creativity would be stimulated and supported by the theory and by inspirational exemplars. Later we introduced two digital prototypes that required students to use simple block coding to change the basic interaction. This understanding allowed students to see the kit we initially introduced in a new way: Rather than using it as a blackbox, they started a process of dis-assembling and re-assembling its components in more creative pieces than those that would have been produced had the students used the prototypes 'as is'. In summary, the effort to understand computing rewarded the students with a stronger creative power.

In discussing how students combined the physical and digital materials, we drew on Devendorf and Rosner's framework of coproductions [24] to position the students' work and how they developed their material practices. Initially, they were sceptical, then open to embracing what the digital could add to their practice and by the end when making their final pieces, they formed a dialogue between the materials and what was technically feasible within their skills. The role of the body in their digital jewellery was central to their designs. Some pieces see the body as the key to activating digital interactions, while others take a critical stance to raise awareness of aspects of self in relation to the body.

To the HCI community, we offered our understanding that can inform future development of DIY toolkits for creatives, and we contextualise our findings within the design and HCI literature in developing toolkits for creatives:

- Theory and practice must be balanced.
- Combining electronics with subject-specific materials and interactions is essential.
- The digital toolkit (pre-assembled circuitry) should be 'dis-assemble-able'.
- Some level of hands-on exploration with technology and coding (possibly block/visual coding) and technical support is required for high-ceiling applications.

We highlight that these recommendations should be considered as a whole package as they work in synergy with one another in the conception and delivery of digital tools and resources for creatives with low-level entry into physical computing. Blackbox toolkits for creatives that completely conceal electronics constrain creativity, as we have found in our research; toolkits for learning basic computing (i.e., Arduino, Adafruit, Seeeduino) offer flexibility, but creatives without a positive attitude to coding or those with a stereotypical view on programming as lacking in creativity and high in complexity, may not see the value of learning basic computer skills. Indeed, the practicalities of using the toolkit should be complemented by theory and inspirational examples to widen thinking and exploration. This delicate balance between theory and practice, ease-of-use and creative freedom is what we investigated in our action research that introduced jewellery students to physical computing.

The research sets the grounding work for digital jewellery education and offers a hands-on perspective and useful tools on how physical-digital materials can be combined in meaningful ways. We argue that engaging with hands-on experiences with digital interactions is important in empowering jewellers to navigate the new design space of digital jewellery. Looking forward to digital jewellery education, we see three ways that jewellery students can embrace micro-electronics, physical computing and digital technology in their practice: to understand the possibilities of the digital material and then work collaboratively with experts to make their ideas happen; to collaborate with interaction/computing students to develop ideas together and inform each other practices; and to acquire enough physical computing skills to implement their ideas themselves.

It would be undoubtedly interesting to explore in future research how our digital jewellery kit gets used by experienced jewellery designers who draw on years of experience, known examples and intuition of working with traditional materials and a traditional design process. However, we cannot expect experienced jewellers to be acquainted with electronics to the level we investigated in this research over a 10-week period and, therefore, the results might not be radically different from our findings with regards to their approach to physical computing. We anticipate that, as jewellers engage more and more with electronics and computing, they will create their own toolbox with jewellery-inspired sensors and actuators [76] and digital-material hybrids (Figure 5) that will create new practices and influence their discipline, as we have seen with conductive threads and sewable boards in the field of e-textiles [43, 44, 61].

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Author's Statement

Digital jewellery is the area of expertise of the first author as she published a review on digital jewellery in 2018 in the Journal for Jewellery Research. She has also published at international conferences: ACM TEI, ACM DIS, ACM CHI, ACM C&C, and Research through Design (RtD). In previous publications she has focused on her practice-based research related to digital jewellery and design methods. This article reports a new direction of digital jewellery research that supports the new generation of digital jewellery makers in developing their original practice. The other authors have supported the research providing technical expertise in the field of interaction design and computing. This work has never been published before, it is not under review, and it is not going to be submitted anywhere else.

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