The Matter of Tools: Designing, Using and Reflecting on New Tools for Emerging eTextile Craft Practices

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Tools, as extensions of hand and mind, prescribe defining properties for a practice. We anchor our tools research within a case study of electronic textiles (eTextiles), combining textile materials and electronic and computational functionality. While the field of eTextiles is expanding into new personal and ubiquitous applications, its tools as productive means, however, are rarely investigated. We fill this gap by both proposing and exploring new tools, aiming at an integrated eTextile craft practice across disciplinary boundaries. Results from a research through design process have been developed into research products and proposed to a wider community of novices and practitioners. Research insights from making, using and reflecting on our new tools show they not only guide habits of making, but also are formative to the understanding of eTextiles as a practice and a field. Their form and function matter for the skills, processes and users, ultimately prescribing the technologies that surround us.

CCS Concepts: • **Human-centered computing** → *Ubiquitous and mobile computing systems and tools*; *Interactive systems and tools*; **Interaction design process and methods**; Contextual design;

Additional Key Words and Phrases: Electronic textiles, eTextiles, smart textiles, DIY, making culture, craft, design, ubiquitous computing, tools, toolkits, research through design

ACM Reference format:
Irene Posch and Geraldine Fitzpatrick. 2021. The Matter of Tools: Designing, Using and Reflecting on New Tools for Emerging eTextile Craft Practices. *ACM Trans. Comput.-Hum. Interact.* 28, 1, Article 4 (January 2021), 38 pages.
https://doi.org/10.1145/3426776

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1 INTRODUCTION

The rising prominence of maker and crafting cultures, paired with ever more affordable and accessible computational technologies, has nurtured rich technology explorations, spanning a wide selection of material and application contexts (e.g., [6–8, 31, 49, 57]). These forms of human–computer interaction (HCI) increasingly include domains and materials not traditionally connected to computer science or electronic engineering disciplines. As a result, in addition to technical understanding, a diverse set of skills in the making and handling of physical materials and design competences is needed to realise technologically and aesthetically compelling interactive artefacts and experiences in these emerging fields.

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1073-0516/2021/01-ART4
https://doi.org/10.1145/3426776

Electronic textiles (eTextiles) (or Smart Textiles), is one such field, researching and developing the integration of textiles with electronic and computational technologies. As defined by Berzowska in 2005: "An electronic textile refers to a textile substrate that incorporates capabilities for sensing (biometric or external), communication (usually wireless), power transmission, and interconnection technology to allow sensors or things such as information processing devices to be networked together within a fabric." [12, p. 4]. eTextile explorations span widely across diverse applications, contexts and settings, using textile materials and techniques to build interactive interfaces and (wearable) electronic and computational artefacts. Some of these developments have reached market availability (e.g., [88]), many others are at a prototypical level, probing new designs and functionalities (e.g., [26, 35, 48]). Beyond commercial applications, combining computational technologies with textile material and craft approaches has been recognised as an important approach for Science, Technology, Engineering, Art and Mathematics (STEAM) education (e.g., [21, 72]), the creation of personal and expressive technologies (e.g., [5, 16, 73, 100]), as well as experimental and artistic explorations (e.g., [24, 83, 91]).

By its very nature, the creation of eTextile artefacts spans across textile, electronic and computational disciplinary boundaries, relying on a combination of theoretical knowledge and practical skills. As fields of making, however, textiles and electronics greatly differ in their histories, in the materials and tools traditionally used, and the routines how to use them. What defines quality within these individual disciplines is fundamentally different: while textile traditions highly value aesthetics, electronics and engineering traditions are predominantly concerned with functionality that does not consider visual or haptic qualities. Consequently, the challenge of such an interdisciplinary field is that all, in this case textile, electronic and computational requirements as well as their interplay with each other, have to be accounted for in the making.

This is why the matter of tools is of specific interest. The word *tool* itself derives from a Germanic root *taw* meaning "prepare" [90]. A tool prepares for other things to happen. The particular function it can carry out defines the making space, and ultimately defines what occupation and pursuits can be executed (successfully). The real and perceived affordances of a tool specify the range of possible activities [68]. A tool is defined as a "device or implement, especially one held in the hand, used to carry out a particular function; a thing used in an occupation or pursuit" [90]. As means of production, tools determine, control and structure the possibilities, shaping the actions that can be performed in any area of making [2]. Through the interaction of the crafter, a tool is brought into relationship with material, "the matter from which a thing is or can be made" [89]. When a tool is an effector or a probe, a material is the substance that may be sensed or altered somehow by the tool [63]. The crafting process is defined by a combination of human control of the tool, the interpretation of the tangible feedback of the material that is felt through the tool, and the nuances in executing changes [67]. In these ways, the tool provides a locus for the skill of crafting [63]. A toolkit is considered a set of tools providing every function needed for a particular process this process by means of its parts' different specifications.

Currently, eTextiles are configured by a diverse and disparate set of tools that reflect the contributing disciplines: textile tools, such as needles and scissors, to manipulate materials like fibres, threads and fabrics; and electronic tools, such as a multimeter or crocodile clips, to connect and measure conductive, often textile, materials that can include conductive threads and fabrics and textile sensors, and electronic and programmable materials, often hardware components, that can include IC boards or LEDs. While attention has been given to designing electronic and programmable components to ease their integration with textile materials [18, 20, 84, 87], the tools however, the productive means that bring eTextile artefacts into being, remain largely unexplored. This is specifically striking, as material and craft-based processes are inherently affected by the approach of their coming into being—depending on the judgement, dexterity and care that makers (can) exercise during the work [92]. In the context of emerging techniques especially, as with eTextiles, new tools could intervene in the fabrication realities within the practice, leveraging new potentials, uses and users.

The research reported in this article takes on precisely this gap. It grew out of a collaborative workshop about speculating new tool ideas for cross-disciplinary practices [55, 74]. It builds on previous work by Buechley and Perner-Wilson looking at the set up of diverse craft practices and how their "different physical materials, tools, and processes can lead to different ways of thinking about, understanding, and constructing electronics" [24], and is motivated by Peppler's call for additional research exploring the range of materials and tools utilised within eTextiles "in order to better understand how cultural expectations materialise as mediated actions and authorise particular tool uses and tool users" [72, p. 281]. Our own previous research of new productive means in the field of eTextiles focused on investigating tools supporting the integration of textile material into electronic making scenarios [82]. Complementing this, we now emphasise the making process itself as defining for a craft practice. eTextiles serve as the case study for the design, use and discussion of new tools towards an integrated eTextile craft practice; the findings though are potentially relevant for the broader field of hybrid electronic craft practices.

At its core, this research inquired into how tools specific to an eTextile practice might look and, extending from this, investigated how the availability of dedicated tools contributes to the configuration of new eTextile craft practices:

- Material and conceptual aspects: How would tools specific to an eTextile practice look? What ideas of practice can a tool embed?
- Process and artefact aspects: How would the availability of distinct tools contribute to the way we consider textile craft routines as relevant for the making of electronic technology? What new routines would emerge from new tools? How would the availability and use of specific tools be reflected in the artefacts?
- Social and cultural aspects: How would the availability of craft tools for eTextile making influence the user group engaging in the electronic making?

Motivated and informed by the first author's practice in the field of eTextiles, we developed *Needlwork Probes: An eTextile Toolset*, as a physical and conceptual argument for a craft practice that integrates textiles and electronics. We see the potential of these new tools in valuing material interactions genuine to textile crafts while simultaneously accounting for electronics requirements. We aimed at holistic and adequate making processes in this emerging field, supporting the production of artefacts that are both functionally and aesthetically satisfying. Once developed to the state of research product [69], we proposed the tools to a broader community of both eTextile practitioners and novices. We did so through workshops, where we introduced the idea of new tools for eTextile making practices and guided people to craft their own tools. Following that, we observed the use of these tools within eTextile practices. In addition, we discussed the roles of tools for emerging practices with a group of experts, to further insights into their (often implicit) practical, social and cultural meanings, and presented them to novices to probe their respective assumptions. Reflecting on our approach and results of this making-centred research approach, we close with discussing broader implications of designing and using new tools within and beyond this specific case study of eTextile.

2 BACKGROUND

Integrating electronics and textiles has been practised and discussed academically for over 20 years, since the mid-late 1990s [40, 42, 86, 87]. Already early work in the field mentioned the potentials—and challenges—of computational technologies expanding into new material domains, both from a perspective of competences in the handling of new materials, and requirements to integrate them with electronic and digital technologies [86, 87]. Since then, academic (e.g., [22, 53, 65, 66]), and later also commercial research and development (e.g., [1, 19, 28, 38, 44, 60, 71]), have investigated sewable electronic components, textile-connectable hardware and wearables, and textiles as a productive material for electronics [84].

2.1 Textiles, Electronics and Computation

Textile crafts are among the oldest crafts practised by humankind, dating back to the prehistoric making of strings. Since then they play essential roles, both functionally and aesthetically, within human experiences. As craft and trade they have shaped human developments and civilisation over centuries [41]. Electricity on the other hand, only started to develop its impact in the late 19th century, digitisation almost another 100 years later. Their different histories, traditions of production and application contexts, distinctly shaped the thinking, understanding and productive means within respective disciplines. While there are important examples throughout history interweaving competences of these three disciplines (as discussed for example in [32, 80, 95]), textiles and (electronic and digital) technologies are predominantly considered to be orthogonal. In the mainstream view, they are also associated with disparate gender stereotypes, connected to different artefact outcomes, tools, settings and skills of production (e.g., [11, 72]), often connoting textile crafts with domestic, female work and electronics with skilled, male tasks. These differences in history, perception and practice of its constituent fields make eTextiles an interesting case study to explore the design and use of new tools. It provides an example of how traditional craft routines and modern electronic technologies can intersect and eventually merge.

eTextiles as a distinct field began to evolve in the mid-1990s, when researchers at MIT and Georgia Tech University started exploring possibilities to combine electronic functionality with textiles. Researchers in the textile department at Georgia Tech embedded conductors and sensing capabilities into the weaving process towards a *Wearable Motherboard* [40]. At MIT, Post and Orth proposed *Smart Fabric, or Wearable Clothing* [86], placing electronic components onto Indian silk organza fabric, that traditionally includes metal threads, using the threads as conductive connections between components. They demonstrated how to "combine sewing and conventional electronics techniques with a novel class of materials to create interactive digital devices", where "all of the input devices can be made by seamstresses or clothing factories, entirely from fabric" [86, p. 168]. While the class of material itself was hardly new—metal threads have been produced and used for thousands of years [36], and even their use as electric conductors has been explored before [81]—its connection to digital devices was new and enabled novel interactions to emerge, as well as new production conditions in the field of interactive technologies.

The focus of early research was to create a "compelling way to create better wearable computers and better physical computing interfaces". [87, p. 841]. Research insights included the demonstration of machine sewn and embroidered sensors as electronic and computational interfaces and introducing a redesign of chip packages to better integrate with textile production. They aimed at enabling an effortless integration of textile and electronics, towards a richer material space supporting the creation of computational artefacts: "Most wearable computers still take an awkward form that is dictated by the materials and processes traditionally used in electronic fabrication [...] ideally, computers would be as convenient, durable, and comfortable as clothing" [87, p. 840].

Since the formulation of theses goals in 2000, research institutes, technology companies and creative individuals, among others, have developed the field further, advancing the aforementioned goal of seamlessly incorporating computational capabilities with textiles. As so-called second skin—materials close to the human body—textiles became an important base for medical and leisure oriented, as well as personal expression-oriented sensor technology (e.g., [26, 35, 58, 88, 99, 100]). As so-called third skin, materials within our surrounding, textiles have been explored as diverse interfaces to the environment (e.g., [12, 15, 64]). Beyond application driven developments, critical and experimental works continue to push the boundaries of textile–electronic interactions and artefacts (e.g., [48, 73, 83]). Many contemporary research and development endeavours focus on process automation, targeted at efficiency and replicability (e.g., [4, 88, 102]. There are though also diverse theoretical and practical arguments for foregrounding a craft approach, both as making process, and as an attitude towards the built artefact (e.g., [10, 24, 85, 101]).

2.2 Electronic Textiles Research and Toolkits

Buechley most prominently contributed to the popular establishment of eTextile crafts [17]. Her developments of the LilyPad series [20], since 2008 under the name LilyPad Arduino, continue to be of high importance. The prime goal was to ease the inclusion of electronic components into textiles. The LilyPad Arduino featured the same computational functionality as previously available Arduino boards, but its physical design, both aesthetically and formally, differs. To better contact with conductive threads, the board was designed in a round shape, featuring sewable connection pads. Instead of the usual blue used in Arduino boards, it was coloured purple. Field studies have shown the potential of attracting new user communities through these design adaptations [23]. Peppler discussed their potential to disclose new practices and concepts otherwise invisible [72]. Beyond the scope of these studies, the presence and wide spread use of the LilyPad Arduino across creative and artistic eTextile applications is a strong sign of the implementation's success. So is the number of other kits and instructions building upon its design, findings and platform (e.g., [47, 50, 53, 54]).

Popular tool kits catering to the wider field of eTextiles (including wearable electronics) such as the LilyPad Arduino [61] or the Adafruit Flora [50] are often sold as comprehensive starter packages. They regularly include a few meters of conductive thread, needles and sometimes conductive fabric—a selection "just enough to get you started" [50] in the fields of eTextiles. Included electronic components have sew-on connection points to facilitate the sewing of the parts onto textile with provided needle and conductive thread. However, generally limiting the textile-specific tools to a needle means that an textile electronic connection can be made, but that the testing or altering of a connection is not accounted for. As such, these kits provide for the fabrication of comparable simple textile circuits, but leave the electronic tinkering, experimenting, measuring and testing to a tool set specific to traditional electronics, and not related to textiles [84]. They include specific components and materials, but no tools to work in a practice integrating textiles and electronics.

A look at online instructions (e.g., [33, 43]) and instructional books (e.g., [25, 37, 45, 47, 59, 70]) shows that they also predominantly rely on conventional electronic and textile tools in their introduction of tools needed. Consistently mentioned are electronic tools such as the multimeter and crocodile clips, essential tools in electronic prototyping processes. These tools though do not take into consideration the changed material realities and manufacturing conditions of eTextile crafts. Instructions and books specifically focusing on fashion or craft aspects also introduce textile tools such as a seam ripper and pins, among others. These are essential to manipulate textile material, but can not take into account electronic functionality that is simultaneously constructed. This disparate set of tools asks the maker to constantly switch the domain of tools, often at the cost of interrupting the craft process. In not being sensitive to these diverse needs of a new practice, there is the risk of not being able to explore and further develop the distinctive qualities of eTextiles. Even worse is the risk of producing eTextile artefacts that are inferior in functional and aesthetic qualities to their individual contributing disciplines, such as electronics or textile design.

2.3 Crafting Tools and Making Cultures

Tools describe, and to some extent prescribe, a practice on an essentially different level than the work itself, embodying the conditions that make the work possible [2]. They not only make it possible to functionally complete tasks, but often also take on a role of figuratively standing for a practice. Historically established stereotypes might surface, suggesting who uses the tool, in what domain it is used, and what artefacts it brings into being [11]. In the context of electronic making specifically, Peppler identified a need to understand specific design features that are associated with gendered histories of tool use so that we might better be able to design tools in the future [72]. The form, function and cultural embedding of tools cannot be considered neutral because they potentially include or exclude specific experiences, insights and goals, whether explicitly or implicitly [62]. This makes them explicitly interesting for critical intervention.

A craft practice emerges from the ensemble of routines enabled by the tools. In Pye's definition, "[Craftsmanship] means using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making" [92, p. 20]. Craft is furthermore understood as the "desire to do a job well for its own sake" [98]. More than productive reflection, craft is a point of view [63].

In recent years, the field of HCI has seen a turn to craft. Craft processes have been studied to broaden the range of people involved in technology developments and the range of technologies and technology aesthetics produced (e.g., [39, 73, 105]). Craft metaphors and qualities have been studied to inform HCI research and the design of new computational fabrication tools specifically (e.g., [27, 34, 52, 94, 95, 106]). Foundational to our own work, Buechley and Perner-Wilson applied intellectual traditions of crafts to electronics building practices, examining the physical and mental experience of building electronics by hand. They specifically distinguish between an activity of prototyping and crafting, describing prototyping as "a manipulation of abstractions", a discrete focus on ideas and functionality, and discrete components. They oppose prototyping to "crafting electronics" as a more continuous and less abstract process. Their findings suggest craft approaches allow for new applications of, and contexts for, technology, as well as contributing to diversity in engineering and intellectual approaches to the field [24]. We intend to further this through the design of tools specifically affording textile crafts in electronic and computational building practices.

Haraway postulates that "it matters what matters we use to think other matters with" [46]. Transferred to the making of artefacts within an emerging discipline of eTextiles, the availability of tools matters in defining what and how ideas materialise. We argue that in the context of technologies increasingly weaving themselves into the fabric of everyday life [104]—as eTextiles both literally and figuratively—intensifies the need to consider the genesis of these technologies. Buechley and Perner-Wilson proposed *adding* tools, techniques and materials from traditional crafts to the technology maker's palette and vice versa "to multiply creative possibilities" [24]. Expanding on this, we look at *designing new tools* for eTextile crafts, inquiring into how they may open up new practices and concepts to practitioners as well as to the general public.

Through the work presented here, we make a physical and discourse argument for eTextiles as craft practice consisting of tools, skills and processes beyond the sum of the constituting parts and that the tools are implicated in both the skills needed and the processes enabled. Towards that goal, we intervene in current practices by proposing new productive means and investigate prevailing production routines and cultural understandings of—and within—the field through their use. We propose new tools for an active conversation with both textile and electronic qualities [96], fostering the exercise of judgement, dexterity and care during the process [92]. In designing and

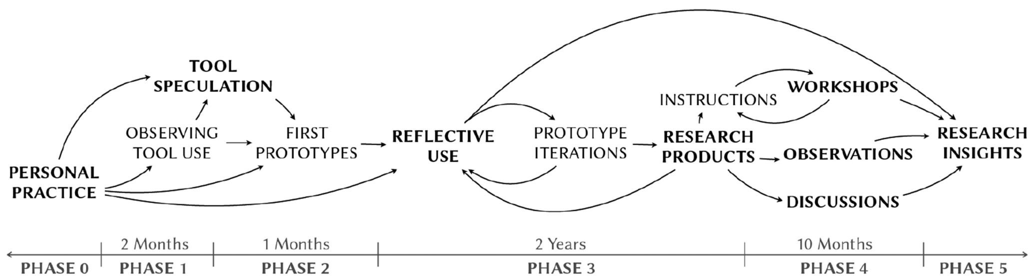


Fig. 1. A graph showing the research through design approach and process along an approximate chronological timeline. Arrows indicate dependencies among the individual steps taken.

deploying these new tools, we aim to evolve eTextiles into an *integrated electronic textile craft practice* and through that diversify approaches, artefacts and communities in the field.

3 METHOD

Our research process covered the iterative design, use and discussion of new tools for eTextiles. Led by the first author and informed by their personal practice in the field of eTextiles, we engaged in the process of designing new tools from a position critical of the status quo, investigating the possibilities for intervention in the field. The starting point was to question existing routines in eTextile making practices, and to speculate about alternatives through functional design proposals, utilising actual and situated design artefacts as a site of critical inquiry [103]. We were inspired by *Critical Technical Practice* [3, 29, 93] in our endeavour to reflect values and assumptions within technical disciplines, and to explore potentials for overcoming technical impasses [93]. Critical Technical Practice propagates the identification of core metaphors within the field and the analysis of what remains marginalised as a starting point for inverting dominant metaphors and embodying an alternative as new technology. Starting with an analysis of how current tools reflect and perpetuate (often unconscious) cultural assumptions and functionally form making practices, we designed, built and evaluated new tools bring alternative values to the fore [97].

In a research through design process, we designed tools as a way to probe and consequently reflect on the implicit values a practice is confronted with through the tools it uses. We intended to approach the design of new technologies not as an end in itself, but as a means to explore assumptions and attitudes that underpin technology creation and interaction [29]. We took a conscious decision at the start to design tools that specifically value and emphasise textile materials and routines. In materialising speculations about new production conditions in electronic making, we aimed at exploring how these might change technology creation and interaction. We then developed these initial designs into research products [69] and included other eTextile makers in their evaluation: inquiring how these tools resonate with them and their practice; and how our explicit focus on foregrounding textile crafts driving the design reflected (on) their practice. Opening up these considerations to others was not just a way to assess the design, but also a way to contextualise and expand our own thinking.

Figure 1 gives a schematic overview of the research process. We briefly describe here the chronological sequence of activities and connect the activities to the sections of this article: Informed by several years of personal making experience in the field of eTextiles by the first author (Figure 1, Phase 0), we started with a self-observation of the use of production and measuring tools (Figure 1, Phase 1). In a workshop together with colleagues active in the field of eTextiles, Hannah Perner-Wilson, Mika Satomi and Ebru Kurbak [56], we explored the possibility space for new tool interventions. A collection of explorations, both from the workshop and subsequent developments,

Table 1. Overview of the Workshop Settings, Participant Numbers and Experience

#	**Workshop Setting**	Location	**Participants**	Practitioners/Novices	**Duration**	**Data Collection**
1	University	Seattle	10	5/5	1.5 h	Notes, Photos
2	Community event	San Francisco	8	5/3	1.5 h	Notes, Photos
3	Community event	France	17	17/-	2 h	Audio, Photos
4	Community event	France	11	11/-	2 h	Audio, Photos
5	Festival	France	14	8/6	2 h	Audio, Photos
6	Festival	London	10	4/6	1.5 h	Audio, Photos
7	University	New York City	11	1/10	1.5 h	Notes, Photos

Workshops took place over 9 months, in five different cities, within the US, UK and continental Europe.

is documented online [74]. Following this initial workshop, the first author individually continued their tool speculations, building a selection of experimental prototypes (Figure 1, Phase 2) and increasingly refined them into functional design proposals guided by the insight gained from personal use for over 2 years (Figure 1, Phase 3). We aimed at a research product fulfilling high functional and aesthetic expectations of a tool, as well as being reproducible as easily as possible. Our approach of designing new tools and developing them into replicable research products is described in *Section 4: Design Process*.

Once the tools were finished to that point, we organised seven workshops sharing our designs and our process of making new tools. We observed participants making and using our tools, and organised discussions about the new tools we proposed (Figure 1, Phase 4). The workshops included both experienced practitioners and novices in the field. Within these workshops, the first author took the role of a participant observer. They facilitated all activities and took written notes as well as photos and audio recordings to capture the discussions and making approaches. These workshops had multiple goals: (1) providing insight into the practical problems of the design and manufacturing of the tool; (2) enabling participants to make their own tools; (3) facilitating a discussion about the meaning of new tools for a discipline that did not yet have any identifiable tools of its own; and (4) providing participants with their own tools, made according to their individual needs. This allowed our tool speculations to become situated design artefacts, which then provided us with use contexts through which we could inquire into the role of tools within eTextile practices in general and crafting practices in particular as they evolved from having new tools available. Details of workshops regarding their duration, place and participants are listed in Table 1 and are further detailed as part of *Section 5: Making Tools*. Following the analysis of making new tools with practitioners and novices, we then analysed the use of the tools within the first author's practice and the practices of a group of practitioner peers, reported in *Section 5: Using Tools*, and we discussed the tools with diverse groups of novices and practitioners as described in *Section 5: Discussing Tools*. In *Section 6: Discussion*, we reflect on our approach, and the insights gained, and also identified limitations and future work. The article closes with the *Section 7: Conclusion*, overviewing the research and its contributions.

In total, 81 participants, both novices and practitioners participated. Four practitioners returned to a workshop a second time. At the beginning of the workshop, participants were presented a consent form detailing the research context. All but one participant signed the form. Comments, data and results from this participant have not been included here. We only collected background information from participants through what they disclosed about themselves during the introduction and discussion phase of the workshop. This informed the separation between practitioners and novices. Throughout this article, we will call people with prior experience and practice with eTextiles as "practitioners", and people without experience as "novices".

Table 2. Overview of the Discussion Settings

#	**Discussion Setting**	Location	**Participants**	Practitioners/Novices	**Duration**	**Data Collection**
1	One-on-One	France	1	1/-	0.5 h	Notes, Audio
2	Ad-hoc Discussion	France	3	3/-	0.25 h	Notes, Audio
3	One-on-One	France	1	1/-	0.25 h	Notes, Audio
4	Ad-hoc Discussion	France	12	12/-	0.25 h	Notes, Audio
5	Focus Group	France	6	6/-	1.5 h	Notes, Audio
6	Ad-hoc Discussion	France	4	3/1	0.25 h	Notes, Audio
7	Demo/Exhibition	London	ca.50	n.a (general public)	2 days/10 h	Notes
8	Demo/Exhibition	Vienna	ca.10	n.a (university public)	1 day/5 h	Notes
9	Demo/Exhibition	Denver	ca.25	n.a (conference public)	2 days/4 h	Notes

Discussions took place in one-on-one settings as discussion between the first author and one participant, as ad-hoc discussions that spontaneously evolved among several participants, and as planned group discussions. In all these contexts, we were aware of the participants background and experience. In extension to this, we also proposed our designs in exhibition settings to a wider audience, demoing their use. In these cases, we noted the approximate number of discussion partners we had an active exchange with, but we did not record their background or any other information about them.

We did not explicitly ask participants about their gender beyond what they revealed in context. From this, we assume all groups were mixed-gender groups. We estimate the percentage of female participants to average between 60 and 85% per workshop. We choose pseudonyms instead of their real names when referencing participants. The same pseudonyms are used throughout the article to reference the same participants.

The integration of these new tools into individual practices was a further point of interest in the research. These observations happened during a week-long meeting of approximately 25 practitioners sharing a studio to work on individual projects, most of them had also participated in one of our workshops, so they had made their own tools before. Participants were informed at the beginning of the week about the research context of these observations and discussions, and signed consent was obtained from all but two. Again, we did not collect nor include data from participants who did not sign the consent form. Data were captured in pictures, videos and observational notes, providing practice-based insight into the use of new tools in eTextile practices. This observation of tool use was complemented by the reflective use of the tools by the first author over the entire research period of over 2 years.

In addition to production-oriented engagements, making and using new tools, we created multiple settings to discuss the proposed tools: as part of the week-long meeting described above, we organised a focus group discussion with six eTextile practitioners who had participated in making the tools and then used the tools in their own practice work throughout the week, to reflect on the tools. During this week, we also engaged in two one-on-one conversations with female practitioners and in three ad-hoc discussions with small groups, one of them being all female (Table 2), that provided a more detailed insight into personal experiences. Beyond this exchange with dedicated practitioners, we presented the tools as part of short-term public demonstration sessions and exhibitions. There we wanted to reach a broader audience that was neither necessarily interested in, nor engaged with eTextiles to probe assumptions among a general public. Details about these different discussion settings, their duration, participant numbers and data collection are listed in Table 2.

The design process and iterations, our own reflective use, as well as participatory making, observing and reflecting the new tool designs, provided us with rich qualitative data probing the role of tools towards an integrated eTextile making practice. Audio and video recordings of the individual sessions (see "Data Collection" in Tables 1 and 2) have been transcribed and connected to written notes and photos of the respective sessions. We conducted a thematic analysis over the combined dataset [13, 14], the results being detailed as part of the evaluation and being the basis to the discussion towards insights gained. Building on these themes, we discuss the potential of developing new tools targeted at novel material interactions for emerging technologies beyond this case study (Figure 1, Phase 5).

4 DESIGN PROCESS: VALUING TEXTILE CRAFTS AS ELECTRONIC TECHNIQUE

In the following, we detail the design of the *Needlework Probes*, an eTextile Toolset. We imagined these tools to become prototypical, yet functional implementations of integrated eTextile crafts. As research products, they would provide a tangible avenue to inquire into the practice.

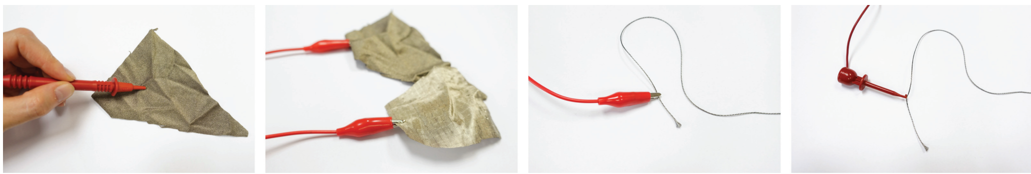
Starting from their reflective observation of their own practice over some months, the first author identified often-used tools to manipulate and construct textile material and to measure electronic properties (Figure 1, Phase 1). The following design approach is driven by referencing textile skills and materials as potential and possible, for some maybe preferable [30], future for electronics. Standard textile tools like pins, needles and hooks, served as the first point of investigation. Their refined shapes have been developed over centuries, allowing for excellent yet gentle contact with delicate fibres to form desired patterns. Being long-established, they are recognised and understood as productive tools of textile crafts. By re-configuring them to be useful in an electronic making context, we wanted to make them a new electronic tool, but simultaneously reference their original crafting context.

In the following, the design iterations are described: we started the process manually assembling first prototypes for initial tests of functionality (Figure 1, Phase 2). We continually used resulting prototypes and evolved successful prototypes towards a more standardised process, including three-dimensionally (3D) printed parts and an increasingly refined selection of primary materials (Figure 1, Phase 3). It was essential for us to make them easily reproducible while at the same time, eliminating as many fault sources as possible to be able to distribute the tools widely. We present our tool designs of *Pin Probes*, *Clip Probes*, *Prototyping Cords* and *Connectable Needlework Tools* for contacting, connecting and making with eTextiles along with detailing the decisions resulting in a reproducible research product. Instructions, as well as download links to design files, are available online [75–79].

4.1 Contacting

Making electrical contact is a prime necessity when building electronic artefacts. Components need to be connected to form a circuit. While making permanent, reliable contact is essential in the final artefact, making temporary but reliable contact between different materials or components is vital for testing and measurement purposes. However, standard electronic probes are often not ideal for the task as the primary material under test when working with eTextiles are conductive textile fibres, threads and fabrics; these are fundamentally different materials compared to traditional electronics.

Figure 2 shows standard electronic probes used on textile material. The standard multimeter probes, far left, can make point contact with a conductive material. However, there is no possibility to attach the probe to the material without holding it by hand. The two pictures in the middle show crocodile (or alligator) clips, a connector often used in electronics for temporarily connecting (to) things. The crocodile clips can connect the diverse textile materials, woven and non-woven fabrics, as well as threads. However, their sharp metallic dents are potentially harmful when working with delicate materials. As they are not designed to close on thin and flexible strands firmly, threads often slip in between the dents, making it hard to establish good electrical contact. The test clip



(a) Multimeter probe (b) Crocodile (or alligator) clips (c) Crocodile clip (d) Grabber

Fig. 2. Standard electronic probes contacting to textile materials: (a) a multimeter probe and (b) crocodile (or alligator) clips contacting fabric, and (c) crocodile clip and (d) a grabber contacting to thread. As standard electronic tools, they can establish electric contact but are not supportive of a craft process. Depending on the material at hand, the contact may be difficult to establish or contacting may strain the textile.

(a) Pin fixed with shrink tube (b) Pin fixed with thermoplast (c) 3D-printed header (d) Pin Probes

Fig. 3. Design of the Pin Probe, starting with a first prototype (Phase 2), iterating towards the research product (Phase 3): (a) connecting a pin with a shrink tube to a silicon-coated thread; (b) using thermoplastic to connect a pin to a conductive thread insulted by a woven cord; (c) 3D-printed header to hold the connection of the pin with a conductive thread, insulted through paracord; and (d) a selection of pin probes in different colours with 3D-printed, snappable, headers.

pictured on the far right is a grabber, usually used on Surface Mount Device (SMD) components. It attaches well to textile threads, but again, is not built to handle delicate materials.

In pursuit of more genuine ways to connect to textile materials, we looked into techniques used in textile crafts to hold material temporarily together. Pins are mostly used for these tasks, for example, when fabrics are held together in the right position before they are sewn, or when potential tailoring changes are marked for testing their effect before the fabric is cut and stitched.

Made out of thin, sharpened metal, pins are pierced through the material to hold it together or place a mark. They have been used to fasten diverse objects or soft material together for centuries, but have an especially strong connotation of being sewing equipment, often seen symbiotically with the practice [11]. They are a precise, firm and temporary way to connect (to) textile material. Being metal, they are also conductive.

We have previously pointed at the benefits and problems of using pins to connect to eTextile artefacts [82]. They can connect firmly, temporarily and pinpointing the material under test precisely, something fundamental in many small detail eTextile works. They can connect to woven fabric without leaving traces. A pinned needle holds on its own, leaving the hands free, something especially important in crafts processes.

Figure 3 shows design iterations towards a *Pin Probe*. One challenge lay in finding suitable pins: while pins are metal, some of them are coated with a less conductive material that is not visible to the bare eye. Such coating might add resistance to the connection, which should be avoided when working in an electronic context. From the variety of pins available, we chose thin, pure steel pin.[1] We chose steel for its conductive properties, and a thin yet sturdy pin so it would not

[1]IRIS®Super Fine Pins. e.g., https://www.schmetzneedles.com/item/IRISreg-Swiss-Super-Fine-Pins-100037.

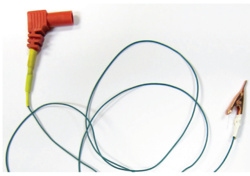
(a) Flat metal clip (b) Normal/Mini Wonder Clips (c) Clip Probe (d) Clip Probe on fabric

Fig. 4. Design of the Clip Probe, starting with a first prototype (Phase 2), iterating towards the research product (Phase 3): (a) a flat metal clip to connect to textile without piercing it; (b) a "Wonder clip" used in patchwork to hold fabrics together (left), and "mini wonder clip" (right). (c) Clip Probe—a mini wonder clip made conductive through the attachment of conductive tape. The soft surface of the conductive tape simultaneously allows for strong yet soft connection. (d) Clip Probe connecting to a metal embroidery on fabric.

leave holes in thin cotton or delicate silk, but still be strong enough to be handled with ease. Another challenge was in attaching the pin to a conductor—designing a handle that is both easy to grasp and not interfering with the textile material, and can house a stable connection. We started the prototyping process soldering a cable to a pin as displayed in Figure 3(a). We then used a thermoplastic[2] to form the joint where the pin connects to the textile cable (Figure 3(b)). Both designs, while functional, were not satisfying concerning their aesthetic and haptic qualities. They were also hard to reproduce. We thus experimented with 3D-printed handles. In early iterations, the top and bottom part needed to be glued together. In the final design, the pin is connected to a conductor and held in place by a custom two-part 3D print that snaps around the pin (Figure 3(c) and (d)). This design is fast and cheap to reproduce, it holds the pin tightly in place and connected to the conductor, and enlarges the pinhead into a flat surface easy to grasp [77]. The choice of colour is only limited by the 3D printing filament available.

While pins can connect to knitted or woven fabrics very well, they might leave holes in non-woven materials (e.g., felt or sheet materials). Also, while they make good contact to threads sewn or embroidered on fabric, it is not easy to connect to free-floating threads. To also address this, we extended the search for eTextile connection possibilities. Figure 4 illustrates the genesis and making of the *Clip Probe*. Here, the goal was to design a non-piercing probe. We started with a flat crocodile clip found at an electronic store (Figure 4(a)). While it did not pierce the fabric, the small surface contact area out of thin copper was not ideal for flexible materials, as the metal would bend easily, but not have the ability to adapt to the textile. Continuing the search in high street textile shops, we found "wonder clips" (see Figure 4(b)) typically used in patchwork to hold fabrics together before sewing them. These clips are not conductive per se. To make them connect electrically, a strip of conductive fabric tape[3] is added to the clipping area, extending to the back of the clip, where it then connects to the conductor. This layer of conductive tape adds a softness to the clipping, connecting exceptionally well to the thin textile material, preventing it from slipping or breaking. In the next design iteration, we switched to a smaller clip size ("mini wonder clips") to better connect to conductive lines close to one another. In the final design, the mini clip is made conductive with conductive tape, the tape at the end of the clip connects to a conductor, held together with a shrink tube as displayed in Figure 4(c) and (d). Colour choices are limited by the colour assortment of the wonder clips and the shrink tube. For the lack of colour choices in shrink tubes, we usually use transparent shrink tubes (6 mm with a shrinking rate 3:1). Mini wonder clips

[2] A plastic polymer material moldable above 70-degree celsius that solidifies upon cooling.
[3] Conductive Fabric Tape 6 mm x 20 m. e.g., https://tinkersphere.com/conductive-thread-fabric/1909-conductive-fabric-tape-6mm-x-20m.html.



(a) Thin cable

(b) Textile cable

(c) Standard banana plug

(d) Screwable banana plug

Fig. 5. Design of cables that integrate well with textile, starting with a first prototype (Phase 2), iterating towards the research product (Phase 3): (a) a thin cable connecting to the banana plug and a metal clip; (b) highly conductive thread insulated with tight yet flexible woven insulation (paracord); (c) textile cable connecting to a standard banana plug with glue and shrink tube; and (d) textile cable connecting to a screwable banana plug.

are a brand item,[4] but cheaper copies in slightly lower but acceptable quality can be found online. Recognising that the production of the Clip Probe includes more individual parts and steps than the Pin Probe, making it harder to assemble, we provided detailed instructions about the length of the conductive tape and the shrink tube to minimise mistakes [75].

4.2 Connecting

Apart from the contact point itself, the electric connection between two materials or between a material and the multimeter is of crucial importance. Contrary to textile qualities, humans do not have senses to judge the electric qualities of a material. To measure the electric properties of components or connections, test leads, as pictured in Figure 2, are needed to connect the object under test and the measuring device, the multimeter. To suit the textile material, the goal was to make the connecting cables as flexible as possible while simultaneously as conductive and as safe as possible. Ideally, this would allow the probe to stay connected to the artefact during the making without hindering the textile work (e.g., by thick cables pushing against a delicate textile artefact), giving instant feedback about electronic measurements. Making a *textile cable* proved to be a balancing act between conductive, insulating and haptic qualities.

Figure 5 shows the development process and material choices. We first tried thin silicon-insulated cables but were not satisfied with their haptic quality and reduced conductivity (Figure 5(a)). In the next step, we tried to make a cable from scratch with a highly conductive thread core and textile insulation around. The search for material suitable for the insulation was difficult. We finally found macramé cords in craft shops; braided textile cords of approximately 5 mm diameter and a hollow inside, through which a conductive thread could be threaded. Still, we were not satisfied with the thickness of the material as it resulted in a quite clumsy textile cable. After another extensive search, thin paracord,[5] similar to the macramé cord but more delicate, was found to be the best material concerning available sizes and colours, their haptics—it feels soft but strong—and material robustness. As a conductor, we decided on a highly conductive thread made out of thin copper strands spun around a nylon core,[6] the best material we found to balance robustness, flexibility and conductivity (pictured in Figure 5(b)) though several strands of thinner highly conductive thread would yield similar results.[7] To interface with a standard multimeter, we used standard banana plugs, finding that screwable banana plugs[8] make for an

[4] Clover Mini Wonder Clips. https://www.clover-mfg.com/product/9/279.
[5] Paracord 100 Type I. https://www.paracord-shop.de/parcord-type-1.
[6] Karl Grimm High Flex 3981, 7x5. http://www.karl-grimm.com/.
[7] Karl Grimm High Flex 3981, 7x1. http://www.karl-grimm.com/.
[8] E-Z Hook, Standard Banana Plug. https://e-z-hook.com/connectors-adapters/banana-plugs-sockets/9202-item/.

(a) Adapting a seam ripper (b) Design iterations (c) Connectable Seam Ripper (d) Connectable Crochet Hook

Fig. 6. Design of Connectable Needlework Tools, starting with a first prototype (Phase 2), iterating towards the research product (Phase 3): (a) adapting a seam ripper to make it connectable, extending the metal tip to the end of the tool, from there connect with a magnet to a connection wire; (b) design iterations of 3D-printed handles for Connectable Needlework Tools; (c) Connectable Seam Ripper, connectable to the multimeter with a mini banana plug; and (d) Connectable Crochet Hook plugged to a multimeter.

especially elegant connection to the textile cable (Figure 5(d)) as they allow for screwing the conductor into the banana plug. For workshops, we decided to use standard banana plugs[9] to keep the costs for workshops low. The conductive thread is squeezed in and additionally fixed with glue and a shrink tube (see Figure 5(c)). Paracord is available by the meter and in diverse colours. The conductive thread we chose is currently only available at a minimum order of 1 kg[10] [76].

Commercial cables and measurement lines are designed for minimal resistance and to withstand high power to guarantee safety for diverse use cases. In our case, the cord is designed to suit the applications in the field of eTextiles: the resistance is reasonably small (0.45 Ohm/meter) for most measuring tasks, and as the field of eTextiles does not usually involve high power, we feel comfortable proposing it in this application context. However, the textile cable does not have a tested and approved power rating.

4.3 Making

In addition to static connections, such as with pins and clips, we designed conventional needlework tools to be electrically connectable and simultaneously serve as a tool for manipulation and testing of the material. A possible scenario evolving from these tools would be to crochet with resistive wool and, during the crocheting, be informed about the electronic qualities of the crochet work. Another scenario would be using a *Connectable Seam Ripper*, using the metal tip to test the connection and, in the case of a faulty connection, to cut it instantly.

Figure 6 displays the evolution of designing electrically Connectable Needlework Tools. As the tips of many conventional needlework tools are metallic, they can directly be used for electric contact. To make the tool connectable, we expanded the conductive tip to the back of the tool. From there it can connect to a textile cable and consequently to a multimeter, or an other probe. Stand alone, the tools can be used as a standard textile tool. When connected, they become electronic probes.

We started the prototyping process making custom handles out of modelling paste, connecting the tip to the back through a wire and attaching a magnet at the end of it (see Figure 6(a))—a magnet being both conductive and easily connectable. When using these tools, we noticed how magnets also attract other metal accessories, such as needles, thus interfering with the making process. We then switched to 2.6 mm mini banana sockets.[11] They fit the size of the tools and could easily

[9]Banana Plug 4mm. e.g., https://www.aliexpress.com/item/32687669826.html.
[10]1 kg/2.2 lbs of Karl Grimm High Flex 3981 material translates to app. 850 meters/2,800 feet for the thicker 7 x 5 stranding, and app. 4,300 meters/14,000 feet for the thinner 7 x 1 stranding.
[11]Mini Banana Socket 2.6 mm. e.g., https://www.conrad.at/de/p/schnepp-miniatur-laborbuchse-buchse-einbau-vertikal-stift-2-6-mm-schwarz-1-st-733873.html.

(a) Multimeter Pin Probe

(b) Connectable Needlework Tools, Needlework Probes

(c) Prototyping Pin

(d) Prototyping Clip

(e) Prototyping Cord with Pin and Clip

Fig. 7. Needlework Probes, the eTextile toolset resulting from our design approach: (a) Multimeter Pin Probes; (b) ensemble of eTextile materials and Needlework Probes including a Connectable Seam Ripper connected to a black textile cable, a Connectable Crochet Hook, Prototyping Pins and a Multimeter Pin Probe; (c) Prototyping Pin; (d) Prototyping Clips; and (e) Prototyping Cords with Pin Probe and Clip Probe ends. Image (b) has also been used to announce several of the workshops we held (see Figure 1, Phase 4).

be integrated with the 3D-printed handles we designed (see Figure 6(b)). The outer form of the 3D-printed handle mimics traditional needlework tools. Their inner details are designed, so they hold the metal tip (e.g., of the crochet hook or seam ripper) at the front and the mini banana jack at the back and connect them electrically through the hollow inside of the handle (see Figure 6(c) and (d)). While a precise 3D printer is needed to print smooth tool handles that are comfortable to use when working with textile and where individual parts fit nicely, once printed, the handles are easy to assemble [78, 79].

4.4 Needlework Probes: An eTextile Toolset

The design process went hand in hand with our reflective practice of using and (re-)designing the tools based on our ongoing experiences. While we started proposing speculation into how new tools for eTextile practices may look, the design process illustrated how it increasingly blended with practice-based insights guiding the design. The result is a set of tools that still reflect the initial approach of valuing textile crafts within electronics, but through their actual use, manifested themselves as productive realities.

— *Pin Probe* describes a pin connected to become an electrical probe. It can become a Multimeter Pin Probe, connectable to a multimeter, pictured in Figure 7(a), or be connected to a Prototyping Cord as displayed in Figure 7(b), (c) and (e).

— *Clip Probe* describes a clip connected to become an electrical probe. Equivalent to the Pin Probe it can be a Multimeter Clip Probe, or be connected to a Prototyping Cord as pictured in Figure 7(d) and (e).
— *Prototyping Cord* describes a textile cable with Pin Probes, Clip Probes or other eTextile compatible probes or connectors at their ends. Prototyping Pins, or Pin Cords, are shown in Figure 7(b) and (c); Prototyping Clips in 7(d). A Prototyping Cord with one Pin and one Clip Probe is shown in 7(e).
— *Connectable Needlework Tool* describes a needlework tool, such as a crochet hook, seam ripper, awl or other, modified to become an electrically connectable tool probe. A Connectable Crochet Hook and Connectable Seam Ripper are pictured in Figure 7(b).

5 EVALUATION

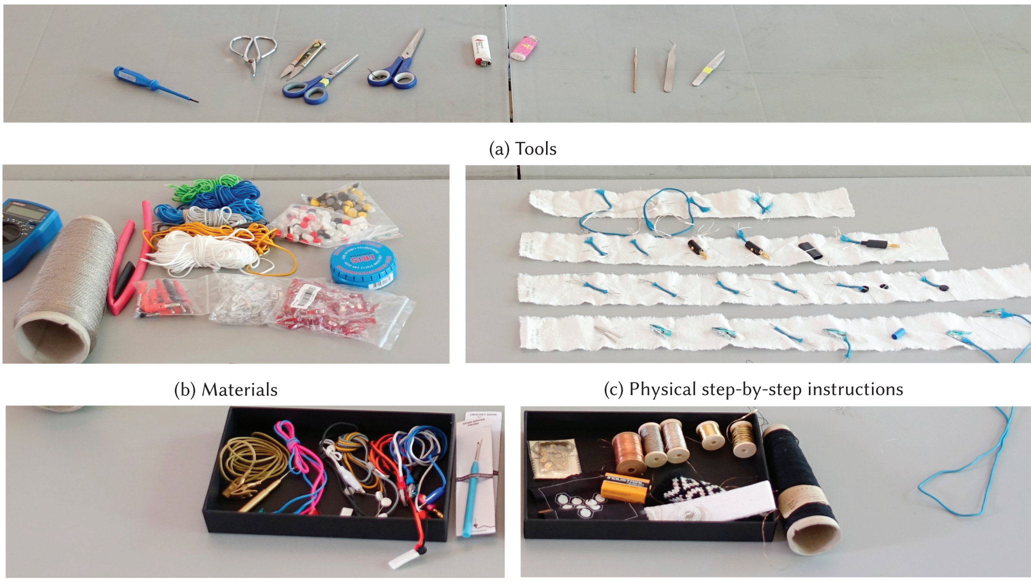
To understand the role and impact new tools have on an emerging practice, we reached out to the community of eTextile practitioners once our tool designs were refined into research products. Proposing our tools to both novices and experts was a way to collect a wide range of feedback through the building, using and discussing these tools (see also Figure 1, Phase 4).

5.1 Making Tools

Over 9 months, we held seven workshops in North America and Europe, inviting people to make tools for eTextiles. These workshops were held after the completion of the design phase, introducing participants first to the research products we developed and then inviting them to make their own tools. After the workshop, people could keep the tools they made to integrate them into their practice potentially. Workshops were hosted in different institutions, among them universities, community meet-ups and festivals, and were targeted at a diverse group of interested individuals. They were advertised before the event on mailing lists and, where possible, through on-site posters. The workshop goal, to make tools for eTextile practices, was announced with the posting, allowing people to participate based on their own interest towards the topic. None of the workshops was part of mandatory or attendance-based programs, and participation in workshops was always free of charge. We, therefore, assume that all participants attended out of personal motivation.

The workshops had between 8 and 17 participants per session. Overall, 51 practitioners and 30 novices participated (see Table 1). The majority had personal eTextile practice (63%), and thus attended with prior understanding of the field and first-hand experience of the challenges connected to the current selection of tools. Two workshops consisted only of practitioners, and the other workshops had mixed groups of novices and practitioners. While we did not ask participants for their age, we estimate the majority was between 25 and 40 years, with the youngest participant being 18 years and the oldest around 70 years old. The workshops lasted between 1.5 and 2 hours. For details about the individual workshops, see Figure 1.

5.1.1 Making Process. The workshops started with an introduction: we presented ourselves and introduced the workshop, and the participants introduced themselves, their background and their motivation to attend the workshop. Novices mostly came out of interest in eTextiles, motivated to become active makers, or out of general interest in technology and design possibilities in eTextiles. Practitioners mostly came with a specific interest to build tools for their practice. Figure 8 shows a typical workshop table with samples, materials, tools and instructions. When working with groups that included beginners, we first talked about basic principles, possibilities and materials used within eTextiles (Figure 8(e)). When working with practitioners only, we directly introduced our tool designs and how we expect them to address current challenges in eTextile making (Figure 8(d)).



(a) Tools

(b) Materials

(c) Physical step-by-step instructions

(d) Finished tools

(e) eTextile sample materials

Fig. 8. Ensemble of a Workshop Table Setup: (a) tools needed in the making process; (b) materials to build new eTextile tools; (c) physical step-by-step instructions attached to white fabric, from top to bottom: textile cable, connection to banana plug, connecting to pin probe and connecting to clip probe; (d) finished tools as inspiration material; and (e) eTextile sample materials. Picture taken at workshop 6.

This introduction was followed by presenting the materials, tools and instructions needed to build the new tools. We introduced the materials: conductive thread as flexible core to a textile cable, a woven cord in different colours as insulating cover for the conductive thread, different probe and connector ends such as banana plugs, pins and clips, custom 3D-printed handles and shrink tubes (Figure 8(b)) as well as tools such as needles, scissors and tweezers to facilitate the making (Figure 8(a)). In the first two workshops, we used instructions printed on paper. From workshop three on, we provided physical step-by-step instructions that showed each building stage of making the tools, the materials needed and the intermediate result after each building step were physically mounted on a strip of fabric: how to thread a textile cable, how to connect to a banana plug, how to attach a pin probe and how to form a clip probe (see Figure 8(c)).

After the general introduction of the materials and instruction into how to replicate our tool designs, participants were free to make their own tools based on the materials available (Figure 9(a)): If asked, we provided suggestions to beginners about what type of tool they might find useful in their future eTextile practice. Practitioners mostly started by copying one of the tools we proposed, and in a further step, started experimenting with new combinations connected to their personal needs. Participants had around 60 minutes to work on their tools. Usually, they started with preparing the cord materials into the desired length and then thread the conductive material through the textile cord to make a textile cable. Each end of the thread would then be mounted to a connector: a plug, a pin or a clip. The physical step-by-step instructions were referenced for how to cut the shrink tubes and conductive fabric tape into necessary sizes. These instructions also served as modular examples of what different probes could be combined into a tool. Most importantly though, the step-by-step instructions became waypoints throughout the making process to diagnose correct or incorrect tool construction through comparing their progress to the built samples

(a) Preparing materials (b) Checking physical instructions (c) Testing Clip Probe on thread

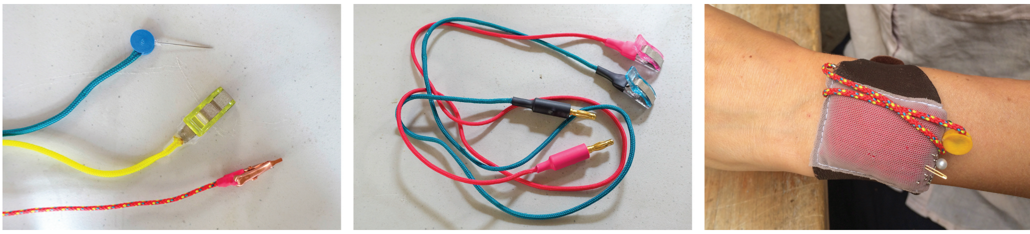
Fig. 9. Tool making process: (a) selecting and preparing the materials; (b) comparing individual steps with the physical step-by-instructions during the making process; and (c) testing the wonder clip on a thin thread.

(Figure 9(b)). Based on these instructions, most participants could identify mistakes and necessary corrections on their own. Participants were also instructed on how to check the quality of their tool with a multimeter. They were encouraged to test any connection they made before moving on to the next step, as well as testing their final tool(s). Towards the end of the workshop, participants presented their results. This was also the time for discussing their experiences in making the tools and how they might use it in the future. They then took their tools with them. They were also allowed to compile a selection of materials to make additional tools at home if they wished to.

The workshops were successful in the sense that all participants could—and did—produce at least one personal tool over the course of the workshop. Most participants closely followed the provided instructions for tool designs: Prototyping Cords with Pin and Clip Probes, or the Multimeter Pin and Clip probes were the most popular tools made, outnumbering the Connectable Needlework Tools by far. Some practitioners also diverted from the suggested designs. They experimented with different combinations and new variations resulting in tools they thought to be specifically interesting for their practice. Examples of these individual design choices are discussed in further depth in Section 5.1.2.

The workshops were also successful with regard to participants, without exception, stating that they enjoyed making their own tools. Practitioners overall could very well relate to the motivation for designing new tools. Still, there were differences in why and what exactly they appreciated. Some generally enjoyed working with new materials and getting to know new techniques and approaches: *"It's really nice to make your own tools! To make textile tools..."* (Tina). To others, the approach to making one's own tools, targeted at personal needs was explicitly interesting. *"It's just nice to have the time to sit down and make these, cause it's kind of amazing how I just deal with what's around me, rather than sit down and create something that should exist that would make my life easier."* (Lucy). Others again were mostly interested in the overall approach, seeing it as a prompt to broader thinking about electronics within textile contexts: *"...the tools that we use are made for electronic and normal materials, plastic, metal, etc... and when you move to textile you feel that there is something missing... so this idea of adding the pins, .. the right grippers to new materials... it's perfect, so... so we need that.."* (Sarah). Beyond eTextile practices, participants also connected the approach of designing custom tools to other disciplines they were personally interested in: *"it has given me ideas on how to measure my biotextiles..."* (Astrid), *"I also want to make paper circuit ones... because that's really useful..."* (Mae). Another participant working mostly with standard electronics reflected: *"but also for normal electronics I think I find pins sometimes really handy [...] for SMD stuff"* (Jack) (comp. Figure 15(c)).

The approach to design one's tools was also seen as being helpful in educational settings, as a possible example and inspiration for design students (Steven), as well as for teaching electronics and eTextiles: *"So it's just like the idea of hacking, you're making yours. It's so clever and it's*



(a) Custom Pin and Clip Cords (b) Multimeter Clip Probes (c) Custom length Pin Cord

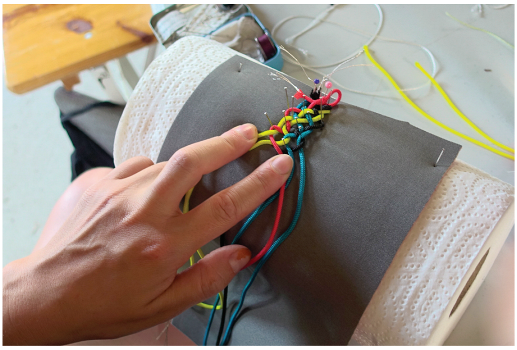
Fig. 10. Tool making design choices: (a) Pin and Clip Cords featuring the pin and patchwork clip we provided, as well as a metal clip that another participant brought to the workshop and the participant built into a tool to use for paper electronics: *"What I really like about that is that the red has the two colours of the other two."* (Mae). (b) Clip probes in custom colours made by an other participant (Michaela), and (c) a Prototyping Cord with a Pin Probe, pinned into a body worn pin cushion.

versatile, so you can use it in many ways, even to customise... even to school to teach and learn it, how it actually works... how you measure, because sometimes it's just taken for granted..." (Sofia). Another participant (Sarah) expanded on that, reflecting on how the making of the tool introduced many concepts and practical skills necessary to the field, such as learning how to make good connections between soft and hard materials, how to measure resistance and how to insulate conductive materials. These comments not only demonstrate the general goal of the workshop was well understood, and well-received, but that making tools prompted general reflections. They also show how participants could engage with the introduced concepts beyond the explicit context of the workshop, both in contextual discussions and in linking the workshop content to their interest in education, or even beyond the field of eTextiles.

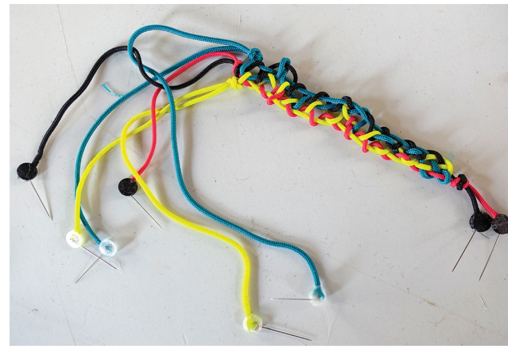
5.1.2 Design Choices. The workshops provided both a selection of tools and materials and suggestions for routines in how to connect them. This allowed participants to realise tools according to their own aesthetic and functional preferences. To also accommodate diverse aesthetic preferences, cords, clips, 3D prints and shrink tubes where provided in different colours.

Choosing the visual appearance of tools was well received, even if for diverse reasons: *"so you can really customise it [...] you can really have your own set, using your own yarn combination..."* (Astrid); *"...I made an Estonian flag!"* (Carol). Apart from personal colour preferences, participants also mentioned the value of having the tools stand out through colour choice from the textile work (Armin), and choosing colour as an indicator for specific connections or functions (Tina and Michaela). Most participants chose red-ish and black-ish cords for multimeter lines, mimicking the accepted colour codes of standard store-bought electronics probes, but decided for more diverse colours for their other Prototyping Cords (see Figure 10 (a)–(c)).

Practitioners focused on the combination of available materials in a way that made personal sense to them, extending from suggested forms. *"so I renewed my crocodile [cables], and I made these [showing his 2-meter long Prototyping Cord with crocodile clips]: I like long crocodiles; When I have a prototype or piece, I always need to connect - but with distance - so I like when its longer than the traditional one, the regular one..."* (Nathan). While most participants expressed discontent with using crocodile clips in their practice, this participant liked them but was not satisfied with the standard length they came in and how their cables did not blend well with textile materials. He replaced the cable with the textile cord we proposed, that is *"much softer"* (Nathan). He also developed his own system of modular eTextile probes, featuring a crocodile clip on one side and one of our proposed tips on the other side: *"because on my multimeter I can plug it, just attach the crocodile to the multimeter and then have a functional eTextile ending..."* (Nathan). His design



(a) Braiding textile cables



(b) Custom Pin Cord design

Fig. 11. The (a) making and (b) result of a participant's custom design: she braided several Pin Cords together through lace-making techniques to produce a bundle of sensing and power lines for easier connection to her prototype. The red and black cord are intended to connect to power, because *"it's easiest to remember with the colour code"* (Tina), the blue and yellow line will connect to sensors.

was later also reproduced by someone else, making a cord to bridge between standard hardware components and textile. Mae ended up using copper clips that another participant brought to the workshop to make a probe that she found worked especially well with paper electronics (see Figure 10(a)). Experimentation during workshops not only resulted in custom combinations of probe ends and varying lengths, but it also resulted in new usage scenarios for tools that we had not presented nor anticipated so far. A participant had in mind to design a cable with an electronic header pin[12] on one side and a pin on the other side. She later concluded: *"first I was going to do a pin to header [prototyping cord], but [...] these [the pins] too go in the breadboard, because they're really strong..."* (Lucy), showing her Pin Cords. In connection with other eTextile materials lying around, one participant discovered how the clips were handy to connect to very thin threads or very thin copper wires: *"It holds really strong! Even the Güterman!"*[13] (Alice) (see Figure 9(c)). While these thin wires would often slip the dents of crocodile clips, they could be firmly squeezed in between the conductive fabric on the pressure points of the Clip Probe.

During the making, participants also discovered that the pin could pierce through the cord materials, making it possible to branch different connections from one cord. *"...you can then also make the lines of a breadboard where you can pin... If you do something on a dummy [mannequin] you can have lines of connectors like flexible breadboards.."* (Tina) (see Figure 11). Monika connected the use of Pin Probes to her challenges of prototyping eTextile projects on the human body, where still many things can change until the final artefact: *"that was always the problem actually, connecting, not making permanent connections [...] so yes, we had lots of problems trying to figure out how to get a wire in there to measure things... Everyone has pins; we just never thought of putting them together."* (Monika). Expanding on the idea of working directly on the body (or a mannequin) as well as the possibility to design custom lengths, Sibyl remarked: *"the length of these tools could not be arbitrary lengths, but may be specific to the body, so you know you have one that reaches from your heart to your toe,..."* In her own design, she was taking into consideration her body as a crafter rather than a body she was crafting for: *"I made short ones, cause I want to carry them with me... they are alligator*

[12] A header pin is an electrical connector consisting of a thin metal stick held in a plastic encasing. A male pin header connects to a female pin socket.
[13] Güterman is a German yarn supplier, known for high-quality yarn.

to pin." (see Figure 10(c)). Another participant explained: *"in fact I would like to make all a medium length and a long length, but this [medium length] is a good start. At home, I'll make more"* (Lucy).

This discussion specifically pointed at the diverse and distinct needs of eTextile practices compared to standard electronic making, to account for the expanded scales and settings eTextiles applications. So, to some extent, the proposal of making tools turned into a probing of current practices, and a provocation to reflect on needs and wishes within the field. A "useful" intervention, at first sight, its use expanded beyond our suggestions through the community of practice it was proposed to.

5.1.3 Assumed Use. Summarising the workshop, the majority of participants stated how they assumed the tool they made would be *"useful"* in their future practice, *"useful"* being mentioned over 20 times within the feedback round of a single workshop. In the context of proposing tools, we consider this highly valuable and positive feedback. It shows that practitioners had no problem relating the use and advantage of the tool to their practice. Their feedback also indicated our tools could address needs that had not been accounted for: needs some were aware of, but still had no means to address, as well as needs that had not even been identified before, the limitations of which people were implicitly accepting and working around. *"So, I did the multimeter to pins, because it's kind of amazing that I haven't made these yet. The alligator clips are for sure problematic when I'm trying to clip to something that's embroidered or really embedded in the textile. So I made something useful I'm sure I'm gonna use all the time"* (Lucy). While speculative at this point, we also asked participants whether they imagined using these tools in the future. Some participants answered enthusiastically they will use the tools they made: *"fuck yeah! Oh my god, are you kidding?"* (Cecilia); *"I'm just doing four jumper cables with the needles - cause I'm going to use these all the time. Super useful!"* (Lucy). However, we also observed caution in participants' anticipation of how much they would change their established practices, or their current workshop setup, in favour of using the new tools they made. An example is this response to our question about whether they will use the Pin Probe: *"I don't know, we'll see, but I anticipate that I might use the double-needle ones more [the Prototyping Pins].. because they are more versatile.. I'm seldom only working with textiles, its usually a mix, and so I probably will have the alligator clips plugged into my multimeter.. use these, and then I might just clip an alligator clip onto a needle to use it as a multimeter probe"* (Angela).

While interested in the Connectable Needlework Tools per se, participants saw a wider field of application for the pins and clips: *"the clips thing, I will use it for sure, but this one [the Connectable Seam Ripper]... - but its cool to have it."* (Steven). Participants thought the idea of the connectable tools was compelling but mentioned it as being much less relevant in their anticipated future use. We assume this is also due to the Connectable Needlework Tools being much more specific to distinct crafting routines participants might not be used to or identify with.

5.1.4 Approaching a Practice Through Its Tools. Unlike practitioners, who immediately related the tools they produced to their practice, novices did not necessarily know anything about the field of electronics, or textiles. They did not have any background experience in the field of eTextiles. For them, making these tools was the first contact with this practice. Still, the workshop was well-received also among novices, and they also all left the workshop with at least one self-made tool. One beginner expressed: *"I think it is a very good beginners workshop, sort of opening to looking at electronic and textiles, so I definitely wanna go and find out about it.."* (Isabel). Several others also expressed that making the tools motivated them to explore the field further.

Novices also commented on the challenges of the workshop, of working with a completely new set of materials: *"I got really frustrated with the fiddlyness, but almost done, I feel like I learned something, so it was good!"* (Carla). The first confrontation with the interplay of different textile and hardware materials can certainly be challenging, but at the same time, it is an essential part of any eTextile making. As the workshop proposed common eTextile materials and routines, it thus can also be understood as contributing to communicating the practice through the making of tools.

We also observed novices who were intrigued by the idea of making their own tools but imagined using them in their field of practice rather than within eTextiles (Anna and Dustin). For them, the approach to broaden the material possibilities when working with electronics, in general, was much more interesting than the concrete solutions addressing textile challenges. *"I will definitely take this with me for the project that I wanna do, cause I just love that it's more gentle - and it will work well with the fine arts"* (Anna).

Beyond the distribution of the designs, the workshops provided a framework for exchange. Opening up the making of tools to both practitioners and novices gave us the possibility of a practice-based exchange with the community across the expertise spectrum. The workshops with novices hinted at what role tools can play for an understanding of a practice. Workshops with practitioners alluded to the role tools can play in facilitating a diverse, and pervasive integration of computational technology with new materials. In the following section, we extend the investigation into tools from making them, to making with them.

5.2 Using Tools

Expanding from assumed and projected use, we looked at the actual use of the proposed tools within a practice of eTextile making. We start reporting on this part of the research in introducing the first author's reflective use over 2 years within their studio practice. We then turn to the observations of other eTextile practitioners. These latter observations took place during a week-long get-together of around 25 eTextile practitioners. At the beginning of the gathering, we held two workshops (Table 1, workshop 3 and 4) in which most of the practitioners participated. For those who didn't, we also brought a selection of finished tools for them to use. Participants over the week worked on individual eTextile projects. In accompanying their making, we were allowed opportunities for in-depth observations of their tool use, workflow and expectations, as well as disappointments with the tools we proposed. We focused on participants' use of the tools they made. If they had requests for new tools emerging from specific tasks within their practice, we together tried to find a solution and build them with or for them.

5.2.1 Developing Practice Through Tools. We start detailing the first author's own experiences of using the Pin Probes when working on embroidering a computer [80, 83]. This embroidery work included connecting coils made out of very thin copper wire[14] to metal threads, with as little resistance as possible. Before using the Pin Probes, a typical scenario was to embroider the connection. The needle would then need to be put down, and the multimeter then picked up. The multimeter would then be used to carefully hold the multimeter probes to contact the golden metal thread and measure the resistance between specific points of interest. If the contact was good enough, the multimeter could be put away, and the needle picked up again to proceed with the embroidery. If the contact had too much resistance, a switch back was needed to improve the embroidery of the connection. As electrical resistance is not detectable through human senses, going back and forth between different toolsets to measure and manipulate the embroidery could take quite a few turns.

A professional embroiderer helped with the gold embroidery tasks. Working on a table-size embroidery frame, the embroider had one hand on top of the frame, one hand below, guiding and

[14]Magnet wire, or enamelled wire, is a copper wire coated with a thin layer of insulation. Here it is used to form a coil as part of a textile relay.

(a) Pin Probes connecting gold embroidery to the multimeter

(b) Clip Probe connecting to very thin copper wire

Fig. 12. Images from an eTextile practice using custom made probes: (a) Pin Probes pinned to an embroidery piece while embroidering, resulting in direct feedback on the multimeter about the established connection; (b) connecting to very fine copper wire with a Clip Probe to test connections.

passing the needle between them to form the stitches, all while minimally moving the rest of her body. A few sessions in, we switched to using the Pin Probes rather than standard multimeter probes. The Pin Probes could be pinned directly into the metal thread and left there without damaging the embroidery. Having completed the first connection with the help of the new probes, the embroiderer stated: *"It's like operating on a live patient! You immediately see the result of your actions [on the multimeter] and can react to it [in the embroidery]!"* (Sabine). She now was able to reflect and act on her stitches not only based on the qualities visible in the embroidery but also their electric quality, simultaneously displayed as a change in resistance on the multimeter (see Figure 12(a)). Being able to observe the changes introduced by individual actions or stitches was essential in transforming the making process from discrete steps of trial and error and tool switching into a continuous conversation with the material at hand—allowing adjustment of the finishing of a stitch based on the real-time insight into its electrical quality. Further along in the making, they also noticed how pinning through the fabric allowed contacting conductive material on the back of the fabric without turning the embroidery around at all. These new routines, resulting from the use of new tools, had noticeable impacts both on the ergonomics of the tasks and the understanding of the effect individual stitches had on the electronic functionality. It saved the disruption of having to switch tools, allowing to simultaneously focus on the textile and electronic qualities of the crafted artefact instead.

We had none of the scenarios we just described in mind when starting the development of the probes. These specific making routines were simply not possible beforehand but instead evolved from having the new tools available in the studio, readily plugged to the multimeter. This allowed us to explore their use as specific needs arose in the course of the practice. Pin Probes plugged to the multimeter, could stay pinned to the fabric when working on it, without stiff cables hindering our movements or the holding of the probes occupying our hands. The possibility to contact material at the back through the fabric also emerged when this specific need arose, and the Pin Probes happened to be the probes plugged to the multimeter. Using the Clip Probe to contact to the very thin copper wire (Figure 12(b)), needed to measure a coils' resistance, is a routine that a workshop participant initially came up with (see Section 5.1.2).

5.2.2 Working on the Body. During the week-long observation of participants, we saw examples of using the tools to work directly on a body—a mannequin, or a person. Angela, for example, started working on a sleeve including textile sensors to detect multiaxial movements of the arm.

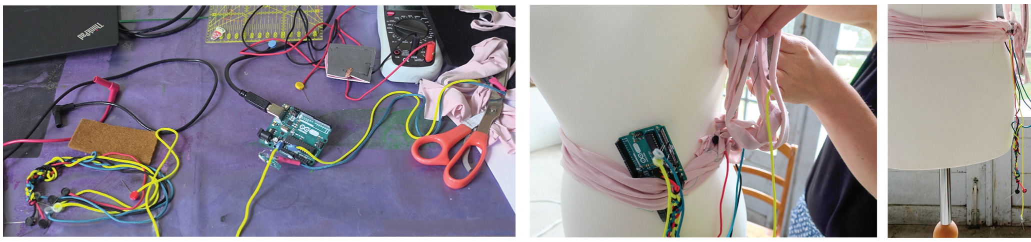
(a) Standard crocodile clips (b) Crocodile/ pin marks (c) Prototyping with Pin Cords

Fig. 13. Usage of the Pin Probe and the Pin Prototyping Cords in the making of a sensing sleeve: (a) standard crocodile clips as well as Pin Probes are used; (b) the difference in marks left in the material; (c) temporary wiring with Pin Cords only, once enough of them were available: Pin Cords connect the sensors within the sleeves to the breadboard during the prototyping phase. The marks in (b) are circled in white (crocodile clip) and black (Pin Probe), corresponding the colours of the probes and circles used as in (a).

Even though she was initially reluctant when making her probes about whether she would use them, she ended up using the Pin Probes to connect them. As she did not have enough of them, she also used crocodile clips to connect to the multimeter (Figure 13(a)). She later showed us her sleeve and the different marks that the crocodile clips and the Pin Probes left on her sleeve: *"look at the difference, its six holes, vs. two small. It [pointing at the crocodile marks] is more crumbled up..."* (Figure 13(b)). We suggested she produce more Pin Probes, so she would not need to use the crocodile clips anymore. She again initially was reluctant. As we had no other cord colours at hand than the ones she already used, she feared she would not be able to differentiate between the individual connections as they would all look the same. As a solution, we decided to make the cords all yellow, but to vary the colour of the 3D-printed handles so they could easily be distinguished from each other. Once she had enough Pin Cords, she exclusively used them: the Pin Cords connected to a prototyping board on one side and the sleeve on the other side. While wearing it, she could observe the changes of the sensor data when moving her arm through a custom software (see Figure 13(c)). She also remarked on the difficulty of connecting with a crocodile clip while wearing a sensor to test it: clipping needs to sandwich the material from two sides, introducing an anomaly to the normal wearing, potentially adding strain to the sensor that would not usually happen. In using the Pin Cords, she could access the sensors in a minimally invasive way, allowing her to measure her prototype under the circumstances as close as possible to the final artefact. She found a new approach to a scenario also Monika described in a different workshop (see Section 5.1.2).

Tina was another participant who ended up intensively using the tools she made. She was working on embedding flexible stretch sensors into a garment. For her, the custom braided Pin Cords she previously made (see Figure 11) proved useful: *"it is really nice to have plus and minus, and then the signal lines ... it's nice to have it all centred. And when I need more [signal lines] I can just add more.."* (Tina). She pierced the Pin Probe into the Arduino board on one side (Figure 14(a)) and on the other side pierced the pins through the fabric or into the knots of a crochet sensor (Figure 14(b)). When unplugging the Arduino (e.g., for reprogramming it), she left the cords hanging on the fabric (Figure 14(c)). The lightweight cords in the meantime did not put too much strain on the fabric, or their stiffness interfere with the soft fabric: *"the flexibility of the material really makes a difference, when you work on a dummy!"* (Tina)

5.2.3 Emerging Use Cases. Previous examples highlighted concrete practices from adopting new tools into use. Being embedded into a shared studio setting as a participant observer also allowed us to get insight into informal settings of tool use, selection and adaptation: in this



(a) Working table with custom Prototyping Cords (b) Working on a mannequin (c) Dangling Cords

Fig. 14. Using custom-made tools for eTextile work on a mannequin: (a) table with working utensils, Arduino board and prototyping cords connected to it; (b) connecting the Arduino to a wearable sensor through the custom designed Prototyping Cords; and (c) disconnected Prototyping Cords hanging lightweight on the mannequin.

(a) Pressing Pin Probe lengthwise (b) Pin Probe piercing fabric (c) Pin Probe piercing plastic insulation

Fig. 15. Examples of emerging scenarios of use: (a) pressing the pin lengthwise onto the fabric to probe the insulation; (b) piercing through fabric to contact to conductive fabric underneath; and (c) using the Pin Probe to contact to the leg of an SMD IC through plastic insulation.

collaborative setting, a few people experimented with a new technique, sandwiching conductive fabric inside non-conductive fabrics (so the conductive fabric is not exposed on the surface anymore) and then tried to measure the now insulated conductor with the multimeter. Observing this, Nathan exclaimed: *"but we have tools for that!"*, rushing to bring Pin Probes to help with the task, piercing through the insulating fabric to the test the conductor (Figure 15(b)). Another participant later reflected how *"Pin Probes go really well with it, because: you can actually leave it sealed up and an insulated circuit and still test it and probe it!"* (Angela).

Miriam, who did not participate in the previous workshop to make her own tools, ended up using Pin Probes she found lying around in the shared studio space. While working on a triaxial matrix of textile sensing lines that she wanted to insulate from each other, she used the Pin Probe—piercing through the fabric to test the connection. In a next step, she also used the Pin Probe, but this time with the pin pressed to the fabric lengthwise, to test if the conductive line is properly insulated from the outside (Figure 15(a)). Others used the Pin Probe to contact an IC chip through its plastic insulation, piercing through the insulation without completely ripping it (Figure 15(c)).

We also observed situations where people actively refrained from using new tools. For example, when Ellen spontaneously needed a prototyping cable to power her colour-changing fabric, Sibyl offered her the Pin Probe that she had ready at hand, it being pinned to her wrist-mounted pincushion (see Figure 10(c)). But Ellen was reluctant to use them. Sibyl promptly confronted her: *"Do you prefer the commercial over the handmade one?"*. Ellen avoided an answer and seemed glad to find traditional crocodile clips for the task quickly. She might have been unsure about how far she could trust the cords Sibyl made, to what extent the specifications of the self-made cable would fit her use. Compared to that, she had used crocodile clips multiple times before and knew what to expect. So, while we could observe a lot of interest and motivation to integrate new tools, this also made us sensitive to dimensions of acceptance and familiarisation in tool use beyond functionality-led choices.

Observing the use of tools in actual making scenarios gave us insights into the practical implications tools can have for a practice, in expanding established working routines or even developing new workflows. It demonstrated how an emerging practice, a craft that does not have established standards for how to do what is shaped by what is around. This leaves space to introduce new tools and consequently enable new results. The reserved reactions to new tools, especially also showed us how important it is that a tool is well understood and trusted. In the following section, we extend the investigation into tools from making and using them, to discussing them. We sought discussions with both practitioners and wider public to reflect on the experiences and the meaning attributed to the tools and their overall importance for the practice.

5.3 Discussing Tools

We engaged in dedicated discussions about the tools in different formats. The first author organised a focus group discussion with eTextile practitioners: a meeting to discuss tools for eTextiles was announced with a set date and time during the week-long gathering in which the tool-making workshops and observations also took place. Participants were invited to take part based on their own interest. The focus group comprised of six people. Beyond that, we engaged in prolonged ad-hoc conversations with individual practitioners during the week-long gathering. Complementing the discussions with practitioners, we reached out to more general public in presenting the tool designs at three short-term design exhibitions. During these exhibition settings, visitors could see and touch the tools and were given explanations of their use. They were also invited to explore the functionality in short hands-on interaction scenarios. These settings allowed us to probe the form and functionality of the tools among non-practitioners and discuss them with a broader public. The focus group and ad-hoc conversations were captured via audio-recording and additional note-taking. During the exhibition settings, notes were taken. In the following, we refer by number to the discussion (see Table 2) to give context to the settings the quoted statements were made.

5.3.1 "It's Symbolic". The visual appearance was one of the first and most discussed aspects among practitioners in the field. They valued the physical form and appearance of the tools, as well as their symbolic aspects. *"[This] embodying of textiles and electric, the interconnection - the multimeter is so much standing for electronics, but then it is a textile cord and the pin. It sort of embodies the practice"* (Sofia, 4), to which Nathan (4) added: *"it's symbolic"*. They identified with the functionality and described tools as being important for their practice beyond their function: *"it's a way to express yourself. Your tools, your medium."* (Kristin, 3).

During the demonstration and exhibition settings, we observed the potential of the tools as signifiers of a practice to novices—their form being recognisable as needlework tools, even if the electronic/technical context in which they are presented was at odds with traditional needlework. To some, the idea and assumed possibilities were intriguing: *"it's very tempting... makes you want to try them out..."* (Ada, 7). To others, the assumed vicinity to textile crafts was a reason not to be interested: *"oh, ok... I'm outta here."* (Peter, 8). Those who stayed and engaged in discussions or hands-on experiences with the tools often expressed how they were not aware that *"these materials"* [conductive textiles] could be used to work with electronic and computational technologies. The different set of skills apparently needed to work with these tools was also repeatedly commented on.

These declarations from novices connect to some of the practitioners' reflections as to why they deem tools to be important for a practice: "*What I learned, is that often the tool is more important for a practice ... They are made to last; they extend over one project"* (Armin, 5). Or, as Cecilia (6) put it: *"tools are what solidify our practice."*

5.3.2 "Tooling Up". Across discussion settings, practitioners often connected the tools to specific productive challenges and the overall lack of tools specific to eTextiles: *"[There is] nothing, nothing on eTextile, really"* (Kristin, 3). They talked about how it was essential to have tools fitting the practice because otherwise, one might relate bad results to one's inability rather than to tools that are not fit for use (Sibyl, 5). The prospect of having dedicated tools was considered necessary for growth within the field: *"... once you have tools for a practice - how does that make that more real? [...] like you can just grow and experiment and play with it more, tinker with it more."* (Cecilia, 6). The role tools can play for (new) people in the field was also considered important: *"having your own tools gives you such ownership of the practice. It's such a moment of identification that is important for new beginners."* (Cecilia, 6).

Tools as a means of identification also came up in another practitioner's comments. To Tina, the choice of displaying or hiding specific tools in her workspace was important in how she understood her practice and wanted her work to be seen. She contemplated how these new tools could potentially satisfy her need of both fulfilling electronic functionality and an aesthetic appearance she felt comfortable showing off next to her work. *"I think with the electronics - I don't like the tactility of the tools, it's all plastic, it's not what I like [...] all electronic stuff for me is in one box... And I think if I'd like it more, you know, you wanna keep it more outside. [...] also like, all the jumper wires, even though they are colourful, they are not something that looks nice. It [the colour] is just useful."* (Tina, 1).

Being able to make one's own tools was also seen by some as a statement of independence, taking action in how they want to shape their making processes (Tina, 5). They appreciated how the process of making the tools taught them new skills and made them aware of basic principles about how they work (e.g., Sibyl, 5; Sofia, 4; and Armin, 5), how it is *"demystifying"* (Michaela, 4) the tools they use, and how it allows them to incorporate personal aesthetic preferences (eg. Sibyl, 5; Tina, 1; and Armin, 4). They mentioned how they got better over time in making their own tools (Angela, 5), but also mentioned that they might still be less likely to trust their self-made tools compared to bought ones: *"my tools need to make it easier for me to work. And I need to be able to work quicker and more reliably with my good tools. So - if I think that I'm gonna get better quality if I buy it, then if I make it, then I buy it."* (Michaela, 5). These concerns connect to the observations we recounted earlier: to what degree does one rely on a new tool, and by extension, to what degree do practitioners trust their skills making them?

Pondering the possibility of eventually being able to purchase these new tools, participants discussed where they would like to buy them. Well-known electronic kit retailers like Adafruit or Sparkfun were mentioned, as well as how they could be displayed in physical stores: whether it would be in well-selected fabric or wool stores or hardware and electronic stores (Tina, Sibyl, Armin, 5). No agreement could be reached on what would be the most appropriate place.

5.3.3 "One of Those Things that are Obvious After You See Them". A visitor to one of the exhibitions, familiar with the field but not a practitioner himself, described the design of the tools as *"one of those things that are obvious after you see them"* (Egon, 9). Similar reactions occurred in other presentation settings. Armin (5) told us how he could not believe that *"this tool"* [the Pin Probe] had not existed before. He told us that, after participating in one of our workshops earlier, he went on to search the internet and order a probe that seemed comparable—a needle probe with a sliding sleeve to pierce through the insulation of a cable. Upon delivery, he realised that this probe was much too big to pierce textile material without harming it and that he could not find anything comparable.

The process of becoming familiar with new tools was also discussed among practitioners. One issue was to have the right tools, and the right number of them available in the workspace. Reflecting on their use, Angela (5) stated: *"so we prototyped with the pin to pins... once we had all, enough pin to pins, we stopped using the alligator clips. We never used them again. We only used the alligator clips when we did not have enough pins"*. Another challenge was adapting to and becoming aware of new characteristics. A few people reported that the probes with pins *"poke you every once in a while"* (Sibyl, 5) or that *"they would pull out"* (Angela, 5). People also had questions about the stability of the tools over long-term use (Alice, 5) and specifications of what power load and routines the tools were designed for, and what would potentially harm them (Tina, 5). While the understanding of a tool often comes with experience, these questions could also be addressed through a datasheet, a well-established form within electronics to communicate the performance of an artefact. Connecting back to earlier discussions, trust in the artefact is probably related to the tool being self-made vs. from a quality brand one trusts, and not primarily connected to its function. During our time of observation, none of the people using the self-made tools or the tools we provided in their work reported any reliability problems, e.g., wrong measurement results because of the tool used. We are also not aware of any harm done by the tools (beyond the poking mentioned above) or any breakage through unintended use.

6 DISCUSSION

The research presented here investigated tools specific to eTextiles and how the availability of new tools targeted at such a hybrid practice contributes to the configuration of eTextiles. We showed what tools specific to an eTextile practice may look like and inquired into the ideas about a practice they embody. The results of our study show that they enabled and embedded new processes within eTextiles, and consequently influence the resulting artefacts. In the following, we discuss these findings in detail in analysing the technical, metaphorical, social and cultural roles of a tool for a practice. We expand the synthesis of the evaluation results with reflections on our contribution to the field as both a practical and a conceptual one. We review our endeavour to functionally augment the tool space, as well as to expand the discourse about the role of tools within emerging practices.

6.1 Potential, Possible, Preferable and Present Tool Spaces

Our research into designing and making tools started from a critical stance towards the existing tool space for eTextiles—the use of disparate conventional textile and electronic tools for an emerging field with novel needs. Our tool speculations focused on how to functionally and figuratively value textile crafts and textile materials in the context of electronics. This manifested in the choice of materials used to build the tools and the deliberate referencing of textile crafts within an electronic tool. We proposed a set of potential tools we deemed preferable for the practice: new probes to better contact to textiles, cords for prototyping connections that are sensitive to delicate materials and productive means for integrated textile electronic making routines. The production of these tools into research products [69] evolved our prototypes from *potential* into *possible* future tools [30]. Developing them from a speculation about what could be, into concrete options, provided the ground for valuable insight into the practice and for understanding the roles of a tool within a practice. In making these tools available to a broader group of expert and novice participants, we could investigate how the tools were understood and received by practitioners and a general audience and examine what would make a tool *preferred* over previously existing ones.

It seems important to note though, that throughout our study, the immediate physical *presence* of tools dominantly shaped how things are done. The sheer availability of conventional electronic and textile tools is what had formed the tool space so far. Placing new tools within the work space equally resulted in their use simply by virtue of being available: the Pin Probes being already plugged to the multimeter, Clip Probes lying around or Prototyping Cords being within reach and available in large enough numbers, resulted in their application, and the discovery of possible benefits. This confirms the importance of the configuration of a tool set as determining, controlling and structuring the possibilities and actions of a practice [2]. However, the continued uptake of our tools when being optional can be interpreted as an expression of participants' preference.

This intervention into the tool space allowed for inquiring into the conditions of the practice on material and conceptual levels. Proposing alternatives to the status quo was a vehicle to stimulate discussions about the current conditions. It provoked active considerations of the dominance of the tools used so far, as well as their limitations. The repeated articulation of how our tool designs addressed existing, but previously unrecognised or unarticulated needs, has shed light on trade-offs of the equipment in use so far and the way tools implicitly embed and prescribe a "right" or "only" way [2]. The questioning in action of these givens revealed the potential of tools to transform the making within this emerging field from being technically possible into craft routines producing aesthetically and functionally preferred results. The availability of dedicated tools can thus be considered an essential step towards solidifying eTextiles as a field in its own right, as one participant called it, maturing from being a poorly equipped extension of other well-established fields.

6.2 Extending the Reach

The designs we proposed oriented along observed routines and established tool use within eTextile practices. The changes explicitly validated textile crafts within electronics, as well as electronics within textile crafts, and aimed at supporting users in exercising their respective skills in the best possible way when being confronted with the new conditions of the emerging field of eTextiles.

As productive means of a practice, these tools physically reach new places, providing new loci for skill [63]. Extending the reach of hand and expanding the understanding of one's actions—being aware of textile and electronic qualities at once draws attention to these qualities as being mutually dependent—creates new awareness of the interplay of material and electronic capacities: direct feedback about the electric conductivity of an embroidered connection empowered the crafter to adapt the stitches while they are being made; piercing through textile material to probe conductive layers underneath enabled the making and testing of new sensors; minimally interfering probes promoted the consideration of natural movements in the design; and working with lightweight prototyping cables directly on a mannequin put the electronic tinkering closer to the work routines of textile tailoring. Use examples showed a number of interesting new possibilities: how less disruptive contacting possibilities might result in finer materials being used, and a higher quality finish of the realised artefacts; how new testing possibilities might further lead to sensor innovation within eTextile work; and how a holistic routine might be faster and generally ease the making of eTextile artefacts.

By making electronic measurement information visible as part of crafting routines, these new tools place tinkering and prototyping into the textile domain and embed textile crafts within the electronic making domain. They allow for a continued dialog with open-ended textile and electronic form and function. As opposed to reacting to discrete measurements taken after the fact, they *integrate* electronic and textile crafts. They enable what Schön called reflection-in-action: providing the maker with the means to "see" the (electrical) change they introduced through their craft actions, making it possible to draw conclusions from these actions in the design situation

[96]. This echoes what Ingold describes as wayfaring behaviour: to be continually responsive to what is continually revealed, being alert to the diverse cues that, at every moment, may prompt an adjustment [51]. It is also defining for the understanding and practising of eTextiles as craft—being able to interpret the material feedback and exercice nuanced changes with dexterity and care [67, 92].

Our observations showed participants recognised that new tools shape their practice in a literal as well as in a figurative sense. Beyond physically reaching new places, the tools expanded metaphorical connotations. Both the making and the talking about tools revealed them as not just productive but also *identity* means within a craft practice. Participants positively related to the real and perceived affordances—the range of possible activities and relationships with the presented tools [68]—describing how they identified with specific practicalities of the designs we proposed, as well as their practice being identifiable through these tools. We could also observe new ways of relating to the tools such as the participant who started "wearing" the Pin Probe. We interpret this act as granting it a status of importance within her practice; it was among the items selected to fit within the small space of her wrist-worn cushion, joining the ranks of traditional needles and pins. It was among the tools she deemed essential to be at hand. Its display on the wrist can also be interpreted as the tool now being a signifier of a sewing practice reaching into new domains, shifting the making of electronic devices closer to the "practices of seamstresses" [86].

Just as practitioners mentioned these tools might provide new opportunities of identification, it could equally be understood as such by a lay public, becoming a symbol of interest—or disinterest—to outsiders. This matches Peppler's call for attention towards particular tool uses and tool users, and specific design features that are associated with gendered histories of tool use [72]. Given the strong stereotypes attributed to textiles and to electronics, proposing tools that facilitate textile electronic making might be seen as feminising electronics. Our tool designs might be reduced to proposing traditional "women's skills" as contributing to a traditionally male dominated discipline of electronics. Rather, the design of the tools is guided by adequately addressing the material space and productive needs towards a professionalisation of the field. They can be understood as feminist though in making visible ways that tool designs configure users and use and the implications these configurations bear for the practice, and in explicitly and intentionally designing for new skills and materials [9, 72] to productively overcome gendered stereotypes. They are a proposition to explore diverse productive conditions, giving voice and choice towards the evolution of the practice. They were aimed at moving past the superficial integration of textiles, enabling the execution of judgement, dexterity and care throughout the process of making. We interpret people declaring our tool designs, once seen, as obvious, or even wondering if or why these had not existed before, as confirmation of them filling a gap as well as being an indicator of the relevance and appropriateness of their design. Examples of use transcending either a textile or electronic practice further showed that they meet a need within contemporary (hybrid) electronic practices.

Conceptually our research expands earlier work in the field: Buechley et al. argued that sewing circuits provide a case for *shifting metaphors* of engineering development from brittle and mechanical solutions towards open-ended possibilities [23, 24]. Based on our research, we argue that tools dedicated to supporting integrated eTextile making routines provide a case for *shifting access* towards and within the field of eTextile making. New tools convey new ideas about the material and possibility space of electronics and facilitate the realisation of them, making concepts visible that otherwise may have been invisible (cf. [72]).

6.3 Mattering Tools

So far we discussed the use of new tools within an emerging craft practice and the broad influence on the practice. Studying the *making* of new tools showed how the production of one's own tools has the potential to expand the understanding of a practice further: it bridges the conditions that bring a practice into being with the practice itself. To novices, it proved to be a valuable first encounter with these conditions and materials in practice. To practitioners, the confrontation with alternative tools gave a way to reflect on the essential matters and routines of a discipline, evaluate how they have approached their practice so far, and challenge limitations they previously accepted. The designs we proposed became a stimulus to ponder further options and starting point for adaptation to individual wishes and needs. It is additionally fitting to the do it yourself approach upheld by some in the field.

While both haptic and visual qualities were essential throughout our design process, we did not foresee the attention participants would give to the tools' appearance. During workshops, participants carefully examined and selected colour choices to make tools they personally found pleasing. We relate this increased attention to a tool's aesthetic both to the previous lack thereof and the aesthetic nature of their craft endeavours. Enjoying the possibility to influence the appearance, participants also made clear that a pleasant exterior alone does not make a desirable tool. For it to be used, it has to be useful, embodying a meaningful blend of form and function. The use of diverse colours specifically shed light on a tool's qualities extending its material impact as effector or probe: beyond just an aesthetic preference, the increased options in colour allowed for better overview when prototyping multiple connections.

We had a prior general understanding of a tools' fundamental role in prescribing a practice (cf. [2]). Their specific influence in eTextiles though only materialised through the practical formulation of new tools. Moreover, while we anticipated some of the new routines during the making of the tools, the majority of use cases and insights only emerged in practice, progressing our speculations into existence. On this basis, our work discussed the importance of equipping emerging practices with tools adequate to their materials, routines and goals—it showed the vast impact resulting from seemingly small changes within the set of naturally accepted, often inconspicuous, tools. While we explicitly focused on designing for eTextiles as a craft practice, as opposed to a prototyping routine or automated process, some of the proposed tools showed the potential to be used across a wide spectrum of manual and industrial routines. Seeing the proposed tools being made and used in diverse hybrid material-electronic practices points at the wider necessity to rethink the means of production of increasingly cross-disciplinary practices relying on (ubiquitous) computational technologies.

To pick up Harraway's formulation again, 'it matters what matters we use to think other matters with' [45]: that is, designing tool alternatives to the status quo matters towards considering the materials and routines core to a practice; proposing new tools matters for the metaphorical, social and cultural anchoring of a practice; using new tools matters for being able to reveal different potentials and functionalities within, and possibly different approaches towards, the practice. And this matters, not least towards enabling emerging hybrid electronic practices and new technological futures.

6.4 Limitations and Future Work

Not all of the proposed tool speculations were received equally, pointing to opportunities for future work. It was essential to us that the proposed tool designs, while made to work well with textile materials, did not exclude other material to be handled through them. The Clip Probes can connect to cables, sheet material, as well as to thread or fabric, the Pin Probes contacts to small surfaces whether textile or on a circuit board, and pierce fabric as well as electronic headers, breadboards and plastic insulation. The lack of a similar versatility might be the reason the Connectable Needlework Tools have not actually been used to the same extent, even though they have been complimented for being a strong visual communicator of an integrated practice. The

Connectable Needlework Tools are fully functional needlework tools, but their application with other electronic material is limited. They are further specifically designed for the hand-crafting of electronic components from textile, which might also be less practised among the people who took part in the workshop. A diversified look at the disciplinary backgrounds of novices, as well as practitioners, and how these backgrounds manifest in the decisions of making and using the Connectable Needlework Tools, or any other tool proposed, might further lead to insights that we could not capture as part of this study.

Our research so far accompanied the ideation, design and implementation of tools, originating from a design approach critical towards the status quo and speculative in its initial formulation. Other researchers and designers most likely would have proposed different tools. We suggest this does not make our approach less relevant but shows the subjective assumptions that shape practices, technologies, and therefore our everyday surroundings. We proposed one alternative to the status quo, literally allowing for new connections to be made within an emerging field of practice. Involving a wide range of participants to use and discuss the tools we proposed revealed their potential to impact the field.

The vast majority of practitioners showed positive sentiments towards the introduction of new tools. We acknowledge, however, that expressing a preference based on early exposure, even well informed, is not the same as actually choosing and using a tool over an extended period. Over time, the tool may become less interesting for its novelty, but will only keep being used if it eases, or in fact improves, working routines. While the research discussed here did not focus on such long-term use and adoption of the tools, the week-long observation of use as well as the first author's own reflective use over more than two years show the potential of the tools to become a permanent element in an eTextile practitioner's tool set.

Future research will aim to more broadly evaluate the long-term availability and use of our tools among practitioners as well as how becoming accustomed to these new tools at the beginning of the engagement with eTextiles might shape novices making practices in the field. Future development research is also needed to evolve the tools into more widely available products, not relying on people having to make them themselves. The example of the LilyPad Arduino most impressively showed the transition from a research prototype to commercial product and the importance of general availability to impact a practice. It further relies on future research to study how insights can be transferred to other tools and machinery in the field, such as, among others, sewing and embroidery machines, weaving looms or the functionality and physicality of a multimeter itself, as well as to other hybrid practices. We would also especially be interested to see others' approaches to interdisciplinary making practices, including a discussion of current practices of tool appropriation, as well as tool designs that embody other preferences than the ones we set.

7 CONCLUSION

In this article, we describe our inquiry and intervention into the tool space of eTextile making practices, a field gaining increasing importance in the making of interactive, personal and ubiquitous computational systems. We employed a research through design approach to new tools. We evaluated them in our own reflective practice as well as through engaging with others in making, using and discussing them. We argue that the availability of more apt tools might further the field as a whole in supporting a more integrated craft practice and consequently afford a better bridging of formerly disparate disciplines towards advancing eTextile practices as well as eTextile artefacts. We started the research and design process in looking at the current state of tools in the field and explicitly valuing textile materials and making routines. Starting from speculation on what tools might prescribe an integrated eTextile practice, we built a selection of tools for replication and use within a community of practitioners as well as novices to the field of eTextiles. The investigation of the resulting tools as functional as well as symbolic objects provided insights into the practical and figurative meaning of tools for the practice: participants appreciated the intervention to the current tool space. They complimented the design verbally, but even more importantly, proved the designs practically by including them as useful tools in their practice.

Looking back at how the field has evolved so far, the material and artefact spaces of eTextiles are discussed a lot for their qualities of being inclusive of new audiences and making approaches. In this context, it is surprising that the actual tools used did not get wider attention so far. As brought up both in the existing literature and in discussions as part of this research, a tool's purpose extends beyond a singular artefact. It brings other artefacts into being. Through the tools we proposed, we shed light on understanding the impact the tool space might have for the development of technologies—especially when becoming increasingly interwoven with everyday life and expanding into diverse material contexts. We provide a practical contribution of designing, building and distributing new tools; empirical insights into use of the tools; and a theoretical discussion about the availability of tools for an emerging discipline. We specifically catered to the field of eTextiles in leveraging the textile material and making routines in the field, and beyond that, hope to contribute more broadly to rethinking the cultures, routines and disciplines that bring interactive computational and electronic artefact into being.

ACKNOWLEDGMENTS

We thank all participants who engaged with our research and used our prototypes and the eTextile community for continuous inspiration. We thank our colleagues Katta Spiel and Özge Subasi for the exchange on early drafts of the article and the TOCHI associate editor and anonymous reviewers for their valuable feedback. Open Access Publication has been supported by the University of Art and Design Linz (Kunstuniversität Linz) and TU Wien.

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Received April 2020; revised September 2020; accepted September 2020