Exploring Computational Materials for Fashion: *Recommendations for Designing Fashionable Wearables*

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Fashion is becoming an inevitable part of wearable devices. Yet, it is not clear how the cross-pollination between computational materials and fashion design might suggest directions for fashion designers who are unfamiliar to this concept. Exploring this territory is important for providing actionable directions to those individuals in exploring fashionable expressions. Therefore, we followed a three-pillared research through design method: (1) a design workshop with 14 fashion design and six engineering students, in which they created seven artifacts by exploring computational and fashion materials, (2) analysis of the workshop outcomes to extract design themes on how computational materials provided interactive opportunities for fashion designers, and (3) semi-structured interviews with 10 wearable design experts from different countries on the results of our analysis. Then, we refined our findings from feedback provided by the experts to finally formulate five design recommendations for designers along with the strategies that they can follow for applying them. In this respect, the recommendations we developed are as follows: (1) giving information through fabric augmentation, (2) defining bi-directional interaction between the contexts and garments, (3) controlling the form of the garments, (4) embellishing surfaces, and (5) supporting the three-dimensional shape of the garment with computational materials.

Keywords **–** Fashion, Wearable Devices, Human Computer Interaction.

Relevance to Design Practice **–** This paper provides design themes and recommendations aiming to be (1) inspirational and guiding for fashion designers who want to incorporate technological components in their designs, and (2) used as a retrospective lens for experienced wearable designers to evaluate their existing creations for exploring alternative paths towards new designs.

Citation: Genç, Ç., Buruk, O.T., Yılmaz, S.İ., Can, K., Özcan, O. (2018). Exploring computational materials for fashion: Recommendations for designing fashionable wearables. *International Journal of Design, 12*(3), 1-19.

Introduction

Nowadays, technological advancements enable computational materials to be implemented on devices—often called *wearable devices* or *wearables*—, which can be worn in the form of garments or accessories. The first theoretical underpinnings for designing wearables (Mann, 1996; Weiser, 1991) prioritized their pragmatic functionalities (i.e., health monitoring, augmented reality applications). Yet, the close proximity of wearables to bodies of users has revealed the need for considering aesthetic and expressive aspects of wearable devices, since, like our conventional clothes and accessories, wearables provide interfaces between our bodies and society (Berzowska, 2005; Juhlin, 2015; Tomico, Hallnäs, Liang, & Wensveen, 2017). Therefore, as the field advanced, more and more HCI studies started investigating the issue from the perspective of *fashion*.

In the human-computer interaction (HCI) field, fashion is usually referred to as the aesthetic appearance of products which make those objects desirable for individuals (McCann, Hurford, & Martin, 2005; Pan & Stolterman, 2015). However, this definition is inadequate, as fashion is strongly related to the aesthetic and symbolic values of the material objects (Wilson, 2003). In that direction, fashion designers focus on pleasing expressive and aesthetic needs of the targeted consumers together with functional needs (Lamb & Kallal, 1992). Traditionally, *textile* is the dominant design material of fashion design (Loscheck, 2009). In that sense, designing *fashionable* garments can be seen as a process of altering the formal state of the textile material (Loscheck, 2009) through fashion production techniques (Sorger & Udale, 2006), including constructing fabrics (i.e., weaving, creating non-woven fabrics), treating fabrics to alter their aesthetic and functional abilities (i.e., dying, embellishing), and constructing silhouettes on bodies (i.e., by draping fabrics, creating darts). However, wearable devices introduced new design materials, namely computational materials, and how to involve/use/create these materials from the perspective of fashion design practice is still underexplored. This is, specifically challenging for inexperienced fashion design practitioners, who are taught crafting and design skills for designing fashionable garments and

Received Dec. 20, 2016; **Accepted** July 24, 2018; **Published** Dec. 31, 2018.

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accessories, yet are unfamiliar with designing interactive objects (Berglin et al., 2007). Inexperienced fashion designers may refer to fashion design students who are very new to the whole field or to experienced fashion designers who are nonexperts in incorporating computational materials.

In this direction, some wearable studies exemplify the new material combinations with the merger of conventional fashion materials (fabrics, leather, threads etc.) and electronic components (i.e. Devendorf et al., 2016; Juhlin, Zhang, Sundbom, & Fernaeus, 2013; Nilsson, Satomi, Vallgårda, & Worbin, 2011). Moreover, many studies provide educational instructions (i.e. Guler, Gannon, & Sicchio, 2016), inspirational tools (i.e. Perner-wilson, Buechley, & Satomi, 2011), and design approaches (i.e. Berglin et al., 2007; Tomico & Wilde, 2015) on how to design fashionable wearables. Yet, there lacks an analysis and actionable directions about exploring computational materials and fashion design in the design process. Comprehension of such actionable design knowledge is needed for nonexpert designers to develop their expertise (Ahmed, Wallace, & Blessing, 2003). To fill this gap, in this study, we aim to reveal a deeper understanding on the opportunities that cross-pollination between computational materials and fashion design can bring to the design process of inexperienced fashion designers. In other words, we aim to answer: *What kind of expressive sources might the interactive technologies provide for fashion practitioners to explore what we wear? How can this inform the design process of fashion designers who are unfamiliar with merging computational materials with their fashion design knowledge?*

As we focus on the *cross-pollination between computational* and *fashion* in terms of fashionable wearables, our research touches on very diverse concepts. The notions of *form* and *expression* are among these critical concepts which are examined through definitions provided by Hallnäs (2011), who defines form as how the materials are physically based on their geometry or how the materials define the space. He also mentions totality of the designers' formal decisions compose an expression that is how the artifact presents itself to people. However, this definition of expression excludes *impression*, which is how people perceive the artifact, and focuses on the definitional logic of the expressions defined by the designer. This differentiation between expression and impression helped achieve the method we used in this study, as we did not intend to examine how fashion design or computational materials might make people feel. In contrast, our intention is to explore how computational materials provide opportunities for fashion designers to design the form and the expression of wearables.

We examined the expressions, and while doing this, placed the material itself as the center of focus. Therefore, we approached *computers as design materials*, which is a trendsetting movement in interaction design (Wiberg, 2015). This movement promotes the exploration of these materials by drawing upon the materials' qualities. For example, computers do not only provide feedback with light sources but also create a visual effect, and do not only sense via a sensor but also modify space, and have a form. As Vallgårda and Fernaeus (2015) suggested, exploration on material qualities of off-the-shelf electronics can help designers to gain knowledge for creating *computational composites* with conventional materials (in our case, common fashion materials such as fabrics, threads, leather etc.).

Therefore, we believe that an approach which takes the off-the-shelf computational materials as a starting point for fashion design may yield results for understanding the meanings of these materials in designing fashionable wearables for designers who are novices in the wearables field. In this direction, our method uses *material exploration* as an *approach in the research through design* (Zimmerman, Forlizzi, & Evenson, 2007), and focuses on *fashionable expressions* that will emerge in the *cross-pollination of fashion and electronics*. Towards this end, in this study, we conducted a design workshop attended by 14 fashion design students and six engineering students to observe the design process of fashionable wearables to gain a deeper understanding about the expressions that can be created in the cross-pollination of computational and fashion materials. The workshop yielded seven fashionable wearable projects, and we analyzed these outcomes by using the *form element categorizations for computational composites* (Vallgårda, 2014). We also analyzed the same

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outcomes in terms of *fashion forming techniques* as employed by Sorger & Udale (2006). Our analysis resulted in design themes that illustrate the cross-pollination between fashion design and computational materials. Then, we turned these themes into design recommendations and discussed them with 10 experts on wearable design from different countries to understand their usefulness and make further refinements. Our discussions yielded productive criticism which led us to refine and broaden the scope of our findings and create the final form of our recommendations for fashion designers to be implemented in the design processes of fashionable wearables.

Computers as Design Materials

For a few decades now, there has been an ongoing debate that criticizes the traditional perspective of HCI, which emphasizes *functionality*, *efficiency* and *usability* over formal and aesthetic qualities (Dunne, 2005; Hummels & Overbeeke, 2010; Redström, 2005). In response to these criticisms, "*the material turn*" (Wiberg, 2015) suggested that we can apply designerly perspective on computers as design materials to form new expressions and experiences (Wiberg et al., 2013).

On that subject, Vallgårda and Sokoler (2010) argued that the properties of computers as design materials cannot be perceived unless they are combined with other materials. Thus, they presented *material strategy* for interaction design in which they described the unique qualities of computational materials as *temporality, reversibility & accumulation, computed causality* and *connectability.* Moreover, when exploring *immaterial* features, invisible and complex qualities of computational materials is another focus in this branch of work (Arnall, 2014; Solsona Belenguer, Lundén, Laaksolhati, & Sundström, 2012; Sundström et al., 2011). These studies have highlighted the importance of hands-on explorations for understanding the complex nature of computers as design materials.

Based on these explorations, researchers argue that interaction design should be seen as a form giving practice. In her more recent work, Vallgårda (2014) suggested terminology for form elements used in interaction design as *physical form, temporal form,* and *interaction gestalt*. Also, by regarding computers as design materials, Hallnäs & Redström (2002) suggested a *leitmotif* to achieve meaningful expressions that "function resides in the expressions of things". This created the basis of their design method named "function-expression-circle," and stands as an alternative to "form follows function" principle.

In HCI education, teaching the design of computational expressions is a challenging subject due to the multidisciplinary nature of the field (i.e., electrical and computer engineers, interaction designers). For instance, Lundgren, Eriksson, Hallnäs, Ljungstrand, and Torgersson (2006) reported that students who do not have a background in programming have difficulties in implementing a working prototype in design processes. Or, for students who do not have a design background, it is difficult for them to explore expressions without considering technological limitations. However, they suggested that working in heterogenous groups and creating high fidelity prototypes (in contrast to conceptual designs), individuals can learn from each other. Also, Vallgårda and Fernaeus (2015) suggested that hands on exploration with even cheap sensors and actuators might help interaction design students comprehend designing well detailed interactive objects.

Taken together, these approaches suggest that prioritizing the exploration of qualities of computational materials in the design process might help inexperienced fashion designers to extract the expressive potential from these materials. Yet, to date, it is not clear how hands-on explorations on the cross-pollination between computational materials and fashion design might suggest actionable design suggestions in designing fashionable wearables.

Guiding Inexperienced Fashion Designers in Designing Fashionable Wearables

Dreyfus and Dreyfus (1986) suggested that novices gain their expertise through a course where they start by understanding the basic facts and features of a skill area in a context-free manner. They implied that, as skill acquisition progresses, the individuals learn from and are guided through specific design experiences and comprehend an automatization of know-how in the specific domain. In this respect, the traditional fashion design curriculum helps students gain skills, and information provides example cases for the students to experience how to explore the textile materials in design processes of fashionable garments & accessories (Sorger & Udale, 2006). Yet, including interactive components to the design process of fashionable wearables proposes new features of computers as design materials (i.e., temporality, computed causality) to be experienced in and guided through the design of fashionable wearables.

In this direction, the emergence of sewable electronics such as the Lilypad Arduino (Buechley & Eisenberg, 2008) enabled craft-oriented explorations on the contribution of interactive technologies to the design of wearables. Following this trend, researchers have focused on creation of instructions, tutorials, and project examples for inexperienced designers to comprehend basic skills of integrating such electronics and programming interactions. For instance, Peppler, Gresalfi, Tekinbaş, and Santo (2014) proposed a method on learning how to engage with soft wearables through a lens of system thinking, which embraced all the elements experienced, understood, and learned regarding an e-textile system to comprehend the overall system. They proposed a toolkit for educators which involved design challenges and instructions for helping educators teach basic craft skills for soft and computational materials. Moreover, Guler et al. (2016) provided a detailed overview on how technology, textile, and fashion design might be blended in wearable designs. Starting from basic crafting techniques of fashion and textile design (i.e., sewing, seeming), they gave examples from inspirational projects on how such techniques can be blended with technology to design wearables (i.e., activated clothing, beauty techs on body).

Also, a unique set of example implementations, illustrating the potentiality of an interactive merge between computational and fashion materials, have been proposed and implemented in workshop structures to inspire novice individuals in their design processes of wearables. For instance, Zeagler et al. (2013) reported a positive pedagogical impact upon introducing their electronic textile interface swatch book, which involved examples of soft circuits, in the beginning of their multidisciplinary workshops series. Moreover, Perner-wilson et al. (2011) presented a workshop series in which authors introduced a diverse palette of craft materials to their participants for creating textile interfaces. They reported that presenting their pre-crafted textile sensors and tinkering with craft materials to reinterpret them during the workshops enabled the participants to understand the technology and to personalize their designs with their existing skills. Researchers have also highlighted the potential of these kits for creating a common language in interdisciplinary design teams (Heimdal, 2009). These approaches are valuable for introducing basic crafting skills and provide inspiration for integrating computational materials to textile materials. Yet, they do not necessarily provide a coherent understanding on how to explore and comprehend new features of computational materials within fashion design processes.

On the other hand, in their paper, Coleman, Peeters, Lamontagne, Worbin, and Toeters (2011) reported some of the courses students undertook to gain understanding on the design of smart textiles. For instance, in Eindhoven University, students are taught a one-week module where they explore the aesthetic opportunities of computational textiles through working on specific techniques (i.e., weaving, knitting). In the Royal Academy of Art the Hague, the students comprehend how to involve computational materials (i.e., LEDs, small motors, thermochromic paints) over the course of seven lessons. In the University of Borås, basic courses on traditional weaving, knitting, and screen printing are augmented with workshops, which include computational materials like optical fibers and thermochromic ink. Moreover, Berglin et al. (2007) examined the possibility of including interaction design methods into fashion design education through a set of workshops. Their main aim was to help fashion design students grasp an understanding on how to analyze and design fashion expressions by relating wearing intentions (what we do when wearing garments) to wearing expressions (what garments do as we wear it). They implemented methods such as using cultural probes (B. Gaver, Dunne, & Pacenti, 1999) to investigate garment use in everyday life, presenting counter examples (Hallnäs & Redström, 2006) to explore alternative expressions to compensate the intention of use of existing fashion items, designing expressions based on specific intentions (Hallnäs & Redström, 2002), and designing the relation between a specific expression and intention through defining interaction styles (Øritsland & Buur, 2000). They reported that including such individual methods clearly raised the level of understanding in fashion design in terms of looking through the lens of interaction design. However, they also reported the complications they faced while describing such abstract theoretical tools to the students in practice.

Embodied approaches in design processes is also suggested in wearable designs. Tomico and Wilde (2016) suggested that tinkering with material on the body and staying in context is useful for designing meaningful wearables. Similarly, Smelik, Toussaint, and Dongen (2016); Kettley, Townsend, Walker, Glazzard, and Corset (2017); and Joseph, Smitheram, Cleveland, Stephen, and Fisher (2017) highlighted the positive influence of focusing on the body, wearing the garment, or developing simple prototypes to understand the interactive opportunities.

Overall, the field provides valuable tools and examples for comprehending crafting skills for merging computational and textile materials. They also provide theoretical and practical approaches for aiding inexperienced fashion designers in designing fashionable wearables. Yet, those studies do not offer a thorough analysis of how computational materials are utilized by fashion designers or provide actionable directions to inexperienced fashion designers for implementing such approaches into fashion design processes. For this, we find adopting an approach which prioritizes the opportunities and affordances of computational materials with fashion design students a useful starting point to understand how such materials might be used to explore expressions in fashion design.

Methodology

As we stated above, we followed a research through design approach. In this respect, our method involved (1) a design workshop, (2) the analysis of the workshop outcome, and (3) semi-structured interviews with international experts (Figure 1). The overall objective of the design workshop was to observe and to understand how material properties of computers are explored by fashion designers in the design process of fashionable wearables. In our analysis on the outcomes of the design workshop, we looked into how the computational composites used for forming the garments, and how the fashion production techniques were incorporated in them. This process yielded design themes and nine recommendations related to these themes. Finally, we sought feedback from wearable design practitioners and scholars experienced in wearable device design to refine our findings and to turn them into actionable design recommendations for fashion designers.

Design Workshop

Participants

14 fashion design students and six engineering students participated in the workshop. Twelve of the fashion design students comprised of third and fourth grade students, and the remaining two were graduate students. The engineering students were third and fourth grade undergrad students. Throughout the workshop, the engineering students were considered as technical consultants and executers, while the design students were in charge of idea generation. This was due to our consideration that the engineering students may possibly restrict the idea generation by prioritizing the technical feasibility. Similar concern has also

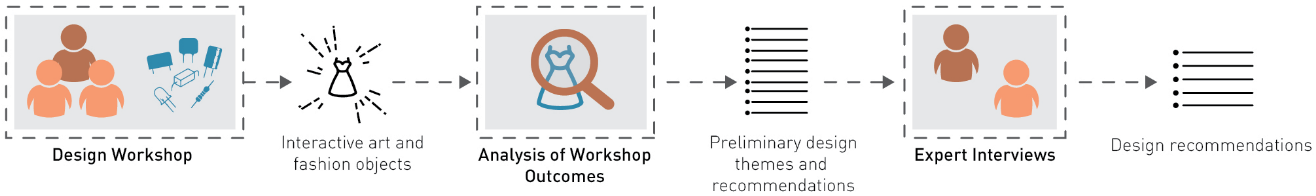

Figure 1. Steps of our methodology.

been highlighted by previous research (Akili, 2015; Cooperrider, 2008; Dym, Agogino, Eris, Frey, & Leifer, 2005): The traditional engineering curriculum limits students to apply technological and scientific principles to problems for converging on one true solution that can be verifiable; whereas the design process also requires a divergent inquiry in which the answers to a problem do not necessarily hold a "truth" value when they first emerge but have potential to create new knowledge.

Three of the authors moderated and remained always available for students during the workshop. Two of the moderators holds a BSc in Industrial Design, and both are studying for their PhD in Interaction Design. The third moderator holds a BA in Fashion & Textile Design and was studying for a Masters in the same area. The other two authors (one a professor in Interaction Design and the other a professor in Textile Art & Design) were present during presentations. The students were also free to receive feedback from the teachers from the Textile & Fashion Design Department of the Mimar Sinan Fine Arts University where they studied.

Procedure

The design workshop comprised two phases. The first phase aimed at enabling fashion design students to freely explore and comprehend the expressive potential of electronic components in combination with fashion materials. For that purpose, the task was given as designing "art" objects independent from any technological or fashion related (ergonomics, context of use etc.) restrictions. The teaching materials included our instructions on implementation of computational materials, our brief presentation at the beginning, and the feedback from professors and conductors during the workshop. Upon starting, we first greeted students and made a brief presentation at the beginning of the workshop. This presentation included the task, information about wearable devices, different design approaches for smart garments, and several distinct examples about how different elements, such as light, motion or 3D forms, have been used in previous studies. This presentation aimed to increase the knowledge of students about the subject and broaden their vision about how to use computational materials as a design material. During the workshop, we encouraged the participants not to limit themselves to the presented examples but to come up with novel ideas by exploring materials. Then, we introduced the electronic components which are designed for crafting wearable devices (such as conductive cloths and threads, single LEDs, LED strips and rings, electro-luminescent wires (EL-wires), tapes and surfaces, microprocessors) and fashion materials (such as a variety of textiles and leathers). In order to increase material diversity, we also included old, non-functioning electronic cards, mechanical parts, and motors disassembled from consumer electronics products.

After introducing the materials, the students individually worked on the materials using a hands-on approach and examined the boundaries thereof. Two of the authors (PhD students in Interaction Design) also helped the students with interactive properties, such as how to light the LEDs and ELs, or how to use conductive clothes and threads. This phase of the workshop did not include the engineering students as we considered they may possibly restrict the ideas with technical feasibility as mentioned in the "Participants" section. After the first exploration phase, the fashion design students framed their ideas and material choices, and formed groups to work on ideas. The ones who wanted to work individually were allowed to do so. At the end, there were seven groups designing "art objects". The production phase was mostly based on exploration. Therefore, although the students had initial ideas to progress from, the whole idea was shaped around the boundaries of the materials. The professors and three graduate students also advised students about design decisions when they asked for recommendations. This first phase lasted for a total of 18 hours over three days. At the end of the workshop, the students presented their "art objects" made of computational composites, which comprised of computational and conventional fashion materials.

The second phase of the workshop aimed at letting the designers transfer their experience from designing an "art object" into the task of designing *"fashion objects"* such as garments or accessories. In this phase, we wanted the fashion designers to base their designs on the "art objects" designed in the first phase. The engineering students of Koç University also participated as supplementary team members in the process by aiding fashion designers with technical inputs. However, we asked the engineering students not to be actively involved in idea generation. Their role (see "Participants" section) was only to implement electronic components in working prototypes with the guidance of the fashion designers, doing the programming and framing the technical possibilities (when implementation was not possible). This phase also lasted for 3 days (18 hours) and the same materials were provided to the students. We also wanted the students to design use-cases for their "fashion objects" and present them with video sketches (Zimmerman, 2005). We used video sketching, since it is a quick method for presenting interaction design decisions. Moreover, with this method, flaws in the design can easily be realized and new ideas can be generated as well as letting designers describe the details of their project which could not be implemented.

The tasks and the structure of the workshop was designed by two of the authors (one of the PhD students of Interaction Design and the professor of Textile Art & Design) by modifying a fiber art course structure to our specific purposes. Previous example results of the fiber art course can be found on the department's website (https://goo.gl/1rz2yQ). The workshop structure was then reviewed by the other authors. At the end of each phase of the design workshop, students presented their concepts via verbal and visual presentations. Their visual presentations included video sketches of intended use cases for their concepts, an implemented prototype, and speculative sketches for the parts that could not be implemented due to technical reasons. All the presentations were video recorded and additional sketches were collected. We also took notes during both workshops.

Outcomes

Overall, the design workshops yielded 8 art objects and 7 fashion objects. In what follows, we present the processes and brief descriptions of the workshop results. More detailed explanations of the design processes can be found in the authors' previous report (Genç, Buruk, Yılmaz, Can, & Özcan, 2017).

Water Drop Bracelet (Figure 2) is an accessory whose pattern is designed to change under the rain, depending on the locations where rain drops contact the bracelet. It also responds to sound, creating different patterns with LEDs placed behind its surface. The designer of this piece created a replica of the artwork Seated Nude by Henri Edmond Cross, which is associated with the pointillism movement, which inspired the form of the LEDs. The designer then created a new composite, though not computational, by placing superabsorbent polymers, which swell when contacted with water, into a bubble wrap. The design student then injected water inside each cell of the bubble wrap and placed a LED strip behind these bubbles to create the desired refracted light appearance.

Reflect the Night (Figure 3) is both a night and a day dress which promises different visual styles by computing the states of the dress. It has a wrapped part in the neck that falls down with the help of servo-motors to turn into a flat poncho when activated by touch. The interior is a retro-reflective surface that reflects the light of LEDs facing it, and reveals shiny patterns of the garment when the wearer dances. During the design process of the art object, the designers discovered that combining retro-reflective fabric and several layers of textiles with light may yield the wavy

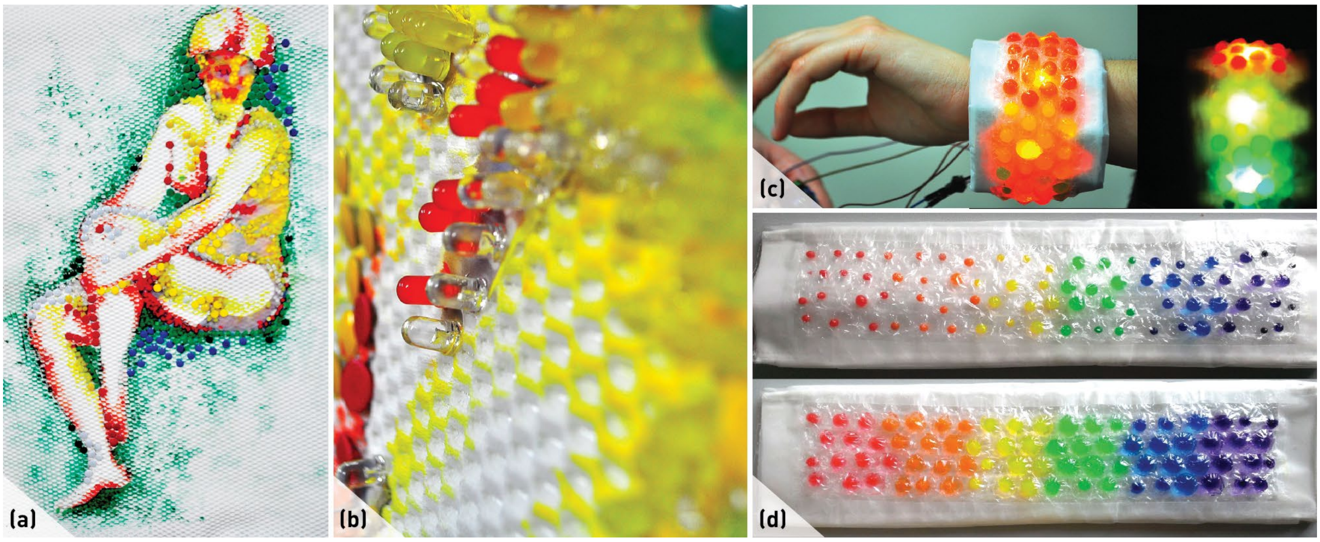

Figure 2. Water Drop Bracelet (designed by Tansu Akın) (a) Art Object, (b) Detail of the Art Object, (c) Water Drop Bracelet and Interaction with Music, (d) Water Interaction with Superabsorbent Polymers.

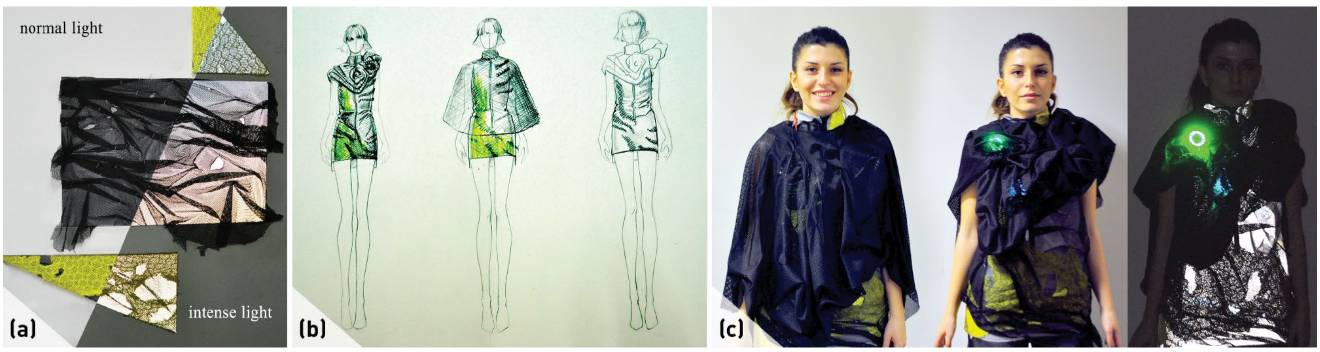

Figure 3. Reflect the Night (designed by Muhammed İloğlu & Yağmur Gevrek) (a) Art object, (b) Sketches of Reflect the Night showing open and closed poncho states, (c) Reflect the Night under normal and intense light.

and shiny look they desired. This resulted in the design of the art object shown in Figure 3-a, from which the same combination of materials were used in their final fashion object (Figure 3-c).

Jellyfish (Figure 4) is a garment whose pattern reacts to outside touches to deter the toucher with the use of speculative soft-robotic cloth pieces that can move around the garment and towards the toucher. In this sense, Jellyfish aims at enhancing self-expression by communicating with the outside with the explicit message: “Do not touch me!”. In the first workshop, the designers explored conductive clothes by ripping them apart to understand their fiber structure. The outermost form they created called to mind jellyfishes, and in the second part of the workshop they defined a function for this jellyfish pattern. They speculated using clothes adorned with micro-robots which could move around the cloth.

Cable Bag (Figure 4) is a bag that is able to become smaller or larger depending on what it holds inside. The bag is woven with a combination of wool, cables, and EL-wires. The designer also speculated using shape memory alloy in the woven structure to be able to directly control the size of the bag. In the first part of the workshop, the designer of the Cable Bag discovered that cables can be interlaced like a chain, and that it may also be possible to better weave them together with the right tools. The designer also expressed that if she were able to easily weave the cables, she may have constructed all the bag from cables without using wool.

Panic Run (Figure 5) is a rain coat for jogging that tightens and loosens depending on the speed of the wearer. The coat is also ornamented with light around the pockets and towards the neck. Yellow meandering parts of the Panic Run were intended to reflect and scatter light emitted from EL-wires. The artwork from the first part of the workshop was structured around the contrast between irregular and wavy shapes of EL-wires and the rigid, structured form of chips and machine parts. The chaotic and city-like (according to designers) form of the artwork inspired them to design a rain coat for jogging in the city. Moreover, the meandering pattern was used in parts of the final design.

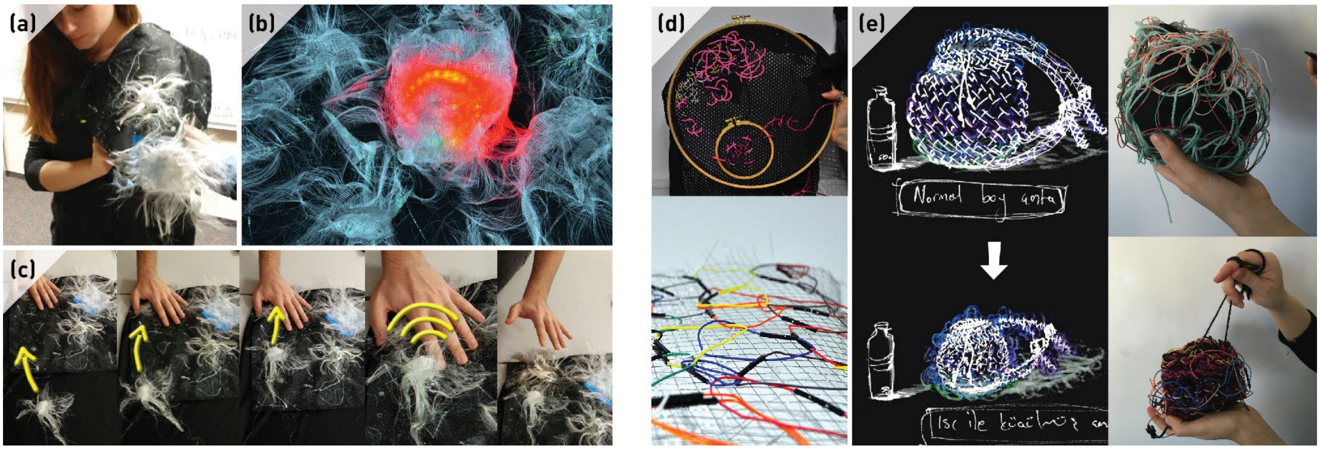

Figure4. Jellyfish and Cable Bag (Jellyfish designed by Ebru Tatlısu & Özde Aybey, Cable Bag designed by Ezgi Tokgöz)
(a) Prototype of Jellyfish, (b) Art object of Jellyfish, (c) Video sketch showing the movement of robotic attachments
(d) Art objects of Cable Bag, (e) Sketches and prototypes of the Cable Bag.

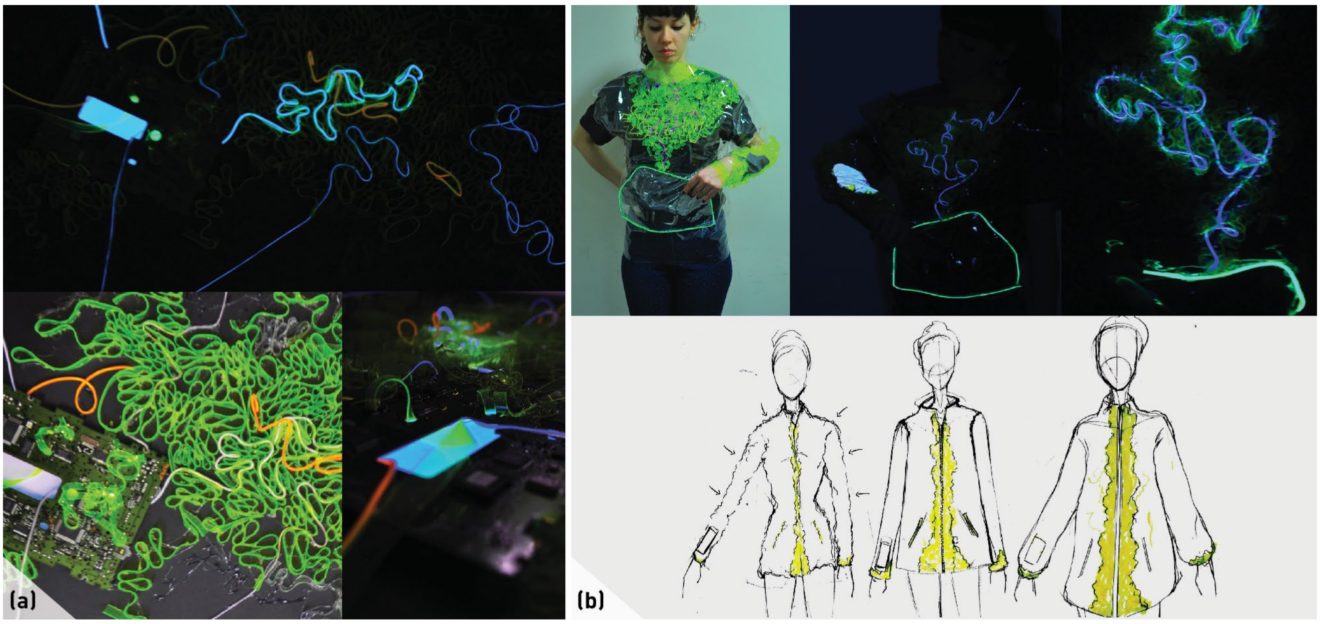

Figure 5. Panic Run (designed by Cemre Eren, İrem Öğütçü & Cansın Gürler) (a) Art object, (b) Prototype and sketches of Panic Run.

Reform Season (Figure 6) is a jacket for different conditions, such as indoor/outdoor, warm/cold weather, by having holes that react to the outside temperature to create different patterns. Reform Season is an exception in our study. The students explored different utilizations of light in the first part of the workshop, however, decided to go with a different final design in the second part.

Bicycle glow is a glove that is designed to aid bikers while navigating around the city by giving direction feedback with lights on its upper surface (Figure 7). The glove has also lights at the edges for increasing visibility, especially while performing turns. The designers of the project explored the relation between textiles and light. Their research resulted in a layered textured textile, the inner layers of which are revealed when a light source is placed behind them. The same pattern was transferred to the final design in the second workshop.

Analysis of the Workshop Outcomes

In the analysis phase, we first reviewed our results from the design workshop, and examined videos of the presentations and sketches for the projects according to the framework drawn from Vallgarda's categorization for *computational composites* (Vallgårda, 2014) and *fashion forming techniques* put forth by Sorger and Udale (2006). Vallgarda's categorization examined computational composites in three sections, which include *interaction gestalt*, *physical form and the temporal form*. *Interaction Gestalt* refers to behaviors of the users/system in relation to others. *Physical form* stands for the shape which is perceived by the human senses, such as material or color, whereas the *temporal form* is about the rhythm or flow of computed changes.

Fashion forming techniques, on the other hand, investigates the subject in three production-based pillars, which include *fabric construction techniques*, *surface treatment techniques*, and *garment construction techniques*. *Fabric construction techniques* include all activities for turning the thread into a fabric (i.e., weaving, knitting). *Surface treatment techniques* are methods which are used for altering or enhancing the fabric qualities (i.e., printing, embellishing). And finally, *garment construction techniques* cover all techniques which can be used for forming the 3D shape of the garments (i.e., using seams, darts, pleats).

After analyzing the outcomes of the workshop with the lens of fashion forming techniques and computational composites framework, we created four main categories, which included "Ambient Interaction", "Surface Alteration", "Modification in 3D Form", and "Material Production". *Ambient Interaction*, built on the *interaction gestalt and the temporal form*, looks into the expressive aspect of clothes, since with new interaction possibilities their interaction with the wearer and the surroundings become visible. *Surface Alteration* refers to dynamic manipulation of the fabric surface via light or different computational materials. This category examines how temporal form of the garment is interpreted with the surface treatment techniques. *Modification in 3D Form* is about the utilization of computational materials to form

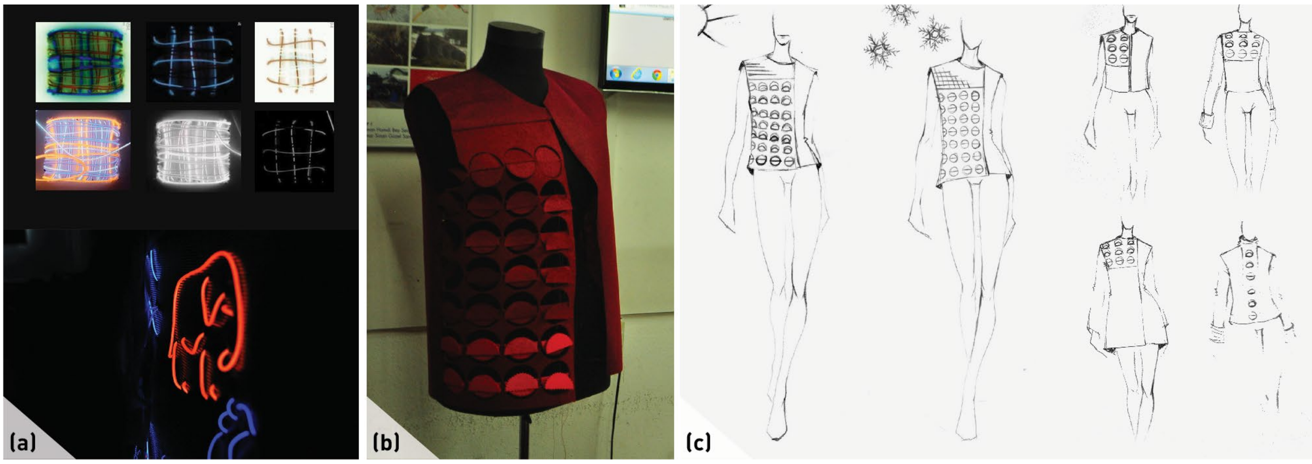

Figure 6. Reform Season (designed by Elif Balta & Selin Topuz)
(a) Art Objects, (b) Prototype of Reform Season, (c) Sketches showing alternatives.

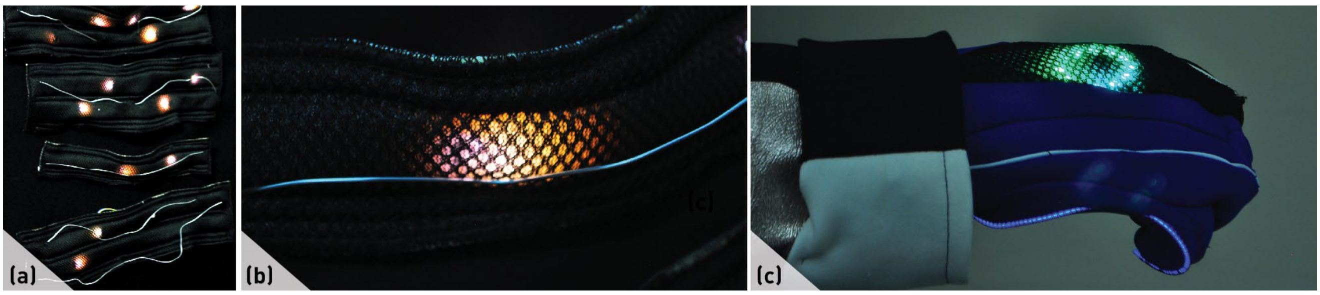

Figure 7. Bicycle Glow (designed by Seydullah Yılmaz, Melis Kabail & Çağla Demirkan)
(a) Art object, (b) Detail of the art object, (c) Prototype of the Bicycle Glow.

and manipulate the 3D shape of the garment. In this parameter, we wanted to examine the *garment construction techniques* with the lens of *physical and temporal form*. Our last category was *Material Production*, which examined how exploration and utilization of computational materials contributed to *fabric construction techniques in relation with the physical form* of the garment. See Table 1 for descriptions of the sub-categories of our framework. The aim here was to decompose and understand how each project contributed to our main areas of investigation. Two of the authors analyzed the data separately, then discussed their findings until they reached an agreement on the results.

The themes presented above helped us to form our arguments for the recommendations that we extracted from them. At the end, we derived nine design recommendations that were presented to the experts in the field for starting conversations about the specific notions exemplified in the recommendations. Our aim was to get feedback on if those approaches might provide information for the designers or the engineers in the field for creating fashionable wearables. To prevent repetition, we have presented the refined recommendations under the "Design Recommendations" section.

Expert Interviews

Participants

For the interviews, we contacted 10 international wearable designers and scholars who have experience in designing wearable devices. Five of the participants were researchers and/or educators, and the other five were professional designers and/or artists in the wearable design field. See Table 2 for the backgrounds of the interviewees.

Table 1. Sub-categories and design themes emerged as a result of analyzing the projects through fashion construction techniques and computational composites frameworks.

Sub-categories	Design themes	Description of the theme	Examples from the design workshop
Ambient Interaction: Bi-directional interaction among the garment, wearer and its surroundings	Contextual triggers	Using the contextual inputs, such as weather temperature, as activation elements for the interactive garments.	- Pace of the runner changing silhouette of the Panic Run - Activation of lights as the wearer dances in Reflect the Night - Interaction with rain drops in Water Drop Bracelet - Pattern change due to the temperature of the environment in Reform Season
	Extending the expressions of the garments to the environment	Using light as a design element which can create tracks and patterns in the environment to connect the garment's expression to the surroundings physically.	- Projection of light through the netted fabric to the walls and the other surroundings in Reflect the Night and the Bicycle Glow
Surface Alteration: Dynamic modifications of qualities of fabric surface via components of computational materials such light or controllable parts	Dynamic surface treatments with computational materials	Integrating computational materials such as lights or movable parts on the surface of the fabric that can be computed to create dynamic alterations.	- Making fabric patterns visible by placing light behind the netted fabrics in Bicycle Glow and Reflect the Night - Change of patterns with light due to the environmental sound in Water Drop Bracelet - Altering the pleats on the fabric with shape-changing materials in Panic Run and Cable Bag
	Embellishing with Computational Materials	Using computational materials as a part of the visual form as embellishments and/or computing the traditional embellishments with computational materials	- Utilization of retro-reflector pieces for projection in Panic Run similar to applique technique - Micro-robotic attachments moving on Jellyfish - Computable cut-outs in Reform Season
Modifying 3D Form: Formgiving and dynamically altering the form and the shape with the use of computational materials	Conveying information through soft materials such as fabrics, textiles and cloth	Defining temporal behaviors of the features of the clothes, fabrics, textiles such as the pattern, form; for giving information	- "Stay away!" message by the moving robotic jellyfish patterns towards touched area in Jellyfish - Navigation information via temporal behavior of light through netted fabric and the bindings in Bicycle Glow - Temperature information via the cut-outs opening or closing in Reform Season
	Changing silhouettes of the garments by controlling the fabrics with computational materials	With the help of computational materials, altering the volume of garments for changing the silhouettes	- Controlling the form of the fabrics with servo-motors to alter the silhouette of Reflect the Night from poncho to clustered state - Loosening or expanding the predetermined pleats by implementing shape-changing materials in Cable Bag and Panic Run
	Using hard computational materials to create structures for the garment	Benefiting the hard or elastic material qualities of electronic components by incorporating them in the garment or fabric construction techniques to support the three-dimensional shape of the garments.	- Creating a rigid and an elastic structure by weaving cables in Cable Bag - Using the hard structure of EL-wires to create a binding in Bicycle Glow
Material Production: Creating new interactive fabric surfaces or using computational materials as base materials for fabric construction	Weaving computational materials	Using computational materials in the fabric structures for increasing the expressiveness of the object.	- Utilizing shape-changing fibers to gradually change the fittingness of the coat in Panic Run - Aesthetic of the form created by the dangling cables in Cable Bag
	Creating non-woven computational composites	Experimenting with computational materials in a way that can inspire the creation of interactive fabric surfaces with non-computational materials	- From inspiration of the form of single LEDs, creation of a new fashionable and interactive surface material by combining superabsorbent polymers and a bubble wrap in Water Drop Bracelet

Table 2. Background of the wearable experts. Mean approx. experience of the participants was 7.05 years.

	Title	Exp.	Background
Bruna Goveia da Rocha	Researcher/ Industrial Designer	5 years	Specializes in wearable technology and interaction design. She is currently a doctoral candidate at TU Eindhoven. Also, a freelance wearable designer.
Camille Baker	Artist/Researcher/ Curator/Lecturer	16 years	Reader at the University for Creative Arts, Epsom in Interface and Interaction, and artistic researcher in the School of Communication Design. She has presented, exhibited, and performed internationally, and her wearable research has been awarded by many institutions (incl. The European Commission - Horizon 2020)
Yulia Silina	Researcher/Jewelry Designer/Artist	5 years	PhD candidate at Queen Mary University of London. Specializes in social wearables. Her works have been selected for many international exhibitions.
Marina Toeters	Researcher/ Lecturer/Fashion Tech. Designer	10 years	Working freelance for Philips Research, Holst Centre, and others. Conducts research and educational activities at Utrecht School of Art, Saxion University, Eindhoven University, and others.
Melissa Coleman	Artist/Curator/ Lecturer	13 years	Curator at "Pretty Smart Textiles" in Holland, Denmark, Austria, and Belgium. Coach at Wearable Senses at TU Eindhoven (2010-2012). She is also an artist and co-host of the "e-stitches" meetup in London and (previously) of "the e-textile workspace" in Rotterdam
Afra Sonmez	Wearable Tech. Designer	3.5 years	Has organized and moderated many workshops on E-textiles and working with fashion designers.
Bushra Burge	Founder/Creative Director/Multimedia Artist	7 years	Founder of an award-winning creative technology company. Most recent artistic and commercial projects have focused on immersive experiences, integrating VR and innovative sustainably made fashion-aesthetic wearables. Her work has been exhibited nationally and internationally
Ezra Cetin	Fashion Designer	5 years	Owns her own fashion brand. Co-creator of many wearable devices, including a collaboration with Intel.
Tuba Cetin	Fashion Designer	5 years	Owns her own fashion brand. Co-creator of many wearable devices, including a collaboration with Intel.
Jason Lin	Designer	1 year	Researches and develops wearable products for people with movement disorders.

Procedure

In each interview, we first stated our aim for this study and presented the outcomes of the design processes from the workshop. After this brief introduction, we presented recommendations extracted separately from the workshop. Each recommendation was presented with its headline, a description of the recommendation, and our proposed strategies for the designers in the context of this recommendation. We also added the evidences from the design workshop as examples from which we derived the recommendations. The aim here was to start conversations about the notions proposed in the recommendations. For example, the recommendation we derived from design themes of *"Contextual triggers"* and *"Extending the expressions of the garments to the environment"* opened up practical and theoretical discussions with the experts about their complex and interesting opinions on context-awareness that helped us refine this recommendation. Each recommendation was discussed within the scope of the following questions: "How would this recommendation affect the creation of fashionable wearable devices when they are presented to wearable designers?", "How useful and valuable is the recommendation on the creation of fashionable wearables based on your experience and observation?", and, based on their criticism on the recommendation, we asked, "How can it be improved?". After getting feedback on each of the recommendations, we asked for their general feedback on the recommendations and built upon these additional opinions.

The interview sessions were conducted either in person or via Skype. Eight of the sessions were individual interviews, one included two of the participants together as these two designers were working collectively on the design of wearable devices at their own fashion studio. Each interview lasted approximately one and a half hours.

Analysis

We recorded the interview sessions and also took notes. For the analysis, we first reviewed the recorded interviews to extend our previous notes. We applied a two-level coding. First, we coded comments to group them according to the recommendations they referred to. We also identified the comments that referred to overall usefulness of the recommendations without addressing a specific one. Afterwards, we incorporated the second level coding that described the details such as "positive", "too specific", and "suggestions". We consulted the video recordings at times where we needed more detailed explanations for our notes. We used "positive" (14 comments) to understand and highlight the useful parts of our recommendations. The "suggestion" (100 comments) tag was for comments that helped us to improve the usefulness of specific recommendations, while "too specific" (42 comments) meant to interpret and refine the recommendation in a way that would target more generalizable design practices. The complete analysis and formulation of end-recommendations therefrom was carried out by the first and second authors who are researchers of interaction and wearable design.

The feedback from the interviews with the experts helped us refine our findings and turn them into more inclusive recommendations that designers can readily adapt to their design processes. Overall, the experts were positive about the recommendations' value and usefulness for designers: For instance, one expert stated, *"I think it (overall recommendations) is extremely useful. It would improve wearable tech design, because it is a different way of looking at a new subject which has not really been disrupted enough."* Besides the positive comments, there were some criticisms and suggestions for improvements, which mainly focused on extending the scope of the implications, simplifying the language, and including external references for the recommendations. Also, the experts suggested additional useful design strategies related to the themes of the recommendations based on either their practical experience or teaching experience. For instance, when we were discussing the recommendation on the theme *"Conveying information through soft materials such as fabrics, textiles and cloth",* one of the experts (designer/researcher) highlighted "the importance given to feedback while designing the abstractness of the information representation through computational fabrics" as a design strategy. Accordingly, we included this in the final version of the recommendation (see 1st Recommendation below). Based on these comments, we refined and formed our recommendations for the design process of fashionable wearables. However, it should be noted that we were not able to address all of the criticisms and suggestions as some of them contradicted each other and others were beyond the scope of this article.

Design Recommendations

In this section, we describe the recommendations for contributing to the expressions of the wearables based on the cross-pollination between computational materials and fashion design.

1. Give Information through the Computational Augmentation of the Clothing

Instead of being restricted by the qualities of fashion or computational materials on the garment, define multi-modal ways of giving information (either for the wearer him/herself or for the viewers) by combining the controllable nature of computational materials with aesthetics affordances of fashion materials and production techniques on garments.

As mentioned in the design theme of *"Conveying information through soft materials such as cloth, textiles and fabrics"*, Panic Run uses the cloth surface for representing information directly, while the Jellyfish and the Reform Season prefer more abstract ways (Figure 8). However, all of these projects used different qualities of fabric forms or surfaces. Our findings indicate that combining the controllable nature of the computational materials with the techniques of crafting garments creates a potential for representing both practical and expressive information by augmenting the language of the garments. Therefore, instead of dictating the qualities of only computational materials or the other way around, this approach creates a new medium by decomposing the features of these two and re-merging them.

Flutter (H. P. Profita, Farrow, & Correll, 2015) dress is a good example for how the integration of computational materials can augment the language of fashion materials with a purpose of conveying information. In this project, the researchers aimed at providing navigational information for persons with hearing loss. They integrated tiny microcontrollers, actuators, and sensors into winglet like embellishments on the garment, by which they augmented these fabric pieces to vibrate and face towards noises in the environment to aid the wearers (Figure 8).

Strategies for designers:

- Explore how the garments can be controlled or altered with computational materials so that the wearer can create the intended meaning in specific contexts.
- Keep in mind that controlled behaviors of the garment are also subject to creation of intended meanings (i.e., cloth moving fast or slow might be perceived aggressive or docile respectively).
- Consider the criticality of the information for defining the abstraction level of the way it is presented.

2. Define Bi-Directional Interaction between the Contexts and the Garments

For defining the relationship between the interactive expressions and the contexts (that the garments are worn), examine the opportunities of both how different contexts can affect the expression and how the garments' expression can alter the contexts.

Garments usually define the close physical space around the body, and the interactions with the clothing are limited to wearing or taking them off, except for interactions such as unzipping or the fabrics' wearing away under environmental conditions. However, our results suggest that the controllable and connected nature of

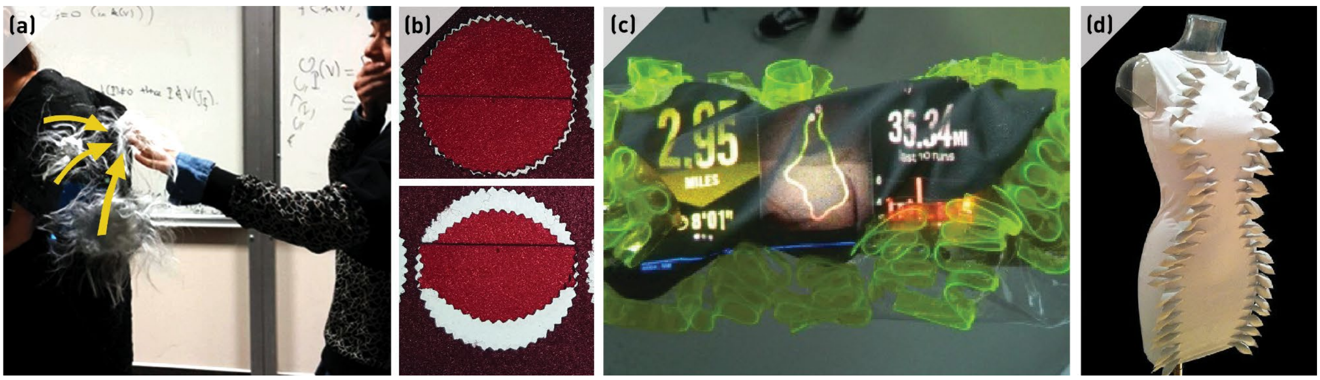

Figure 8. Examples for 1st recommendation
(a) Illustration of moving Jellyfish patterns conveying the information of "Stay Away!", (b) Reform Season's open and closed patterns providing information regarding temperature, (c) Direct information Interface of the Panic Run on the wearer's arm,
(d) Flutter (Profita et al., 2015) dress with winglets for displaying information to its wearer by heading towards the noises.

the computational materials enable the garments to give expressive responses to a wide range of triggers that are readily available in the variety of contexts (i.e., physiological data, environmental data, gestures), while also providing opportunities of garments affecting the contexts (i.e., surfaces around, other people).

The evidences which pointed to this recommendation was mentioned in the design themes of *"Contextual triggers"* and *"Extending the expressions of the garments to the environment"*. The project "Reflect the Night" is a good example of the bi-directional interaction between the garment and the contexts that the garment is likely to be worn. Despite its regular look during daytime, in a night-club context, it is triggered by the music and the body movements of the wearer, affecting the environment by projecting its light patterns and extending its expression towards the environment (Figure 9).

As an external example of this recommendation, we can name the Butterfly Dress (Landau, 2014), which is a dress that has robotic-butterfly-like-embellishments on the top part of the dress. By using the implemented proximity sensor on the garment, the garment reacts to an approaching person by activating the butterflies to fly away from the garment (Figure 9). The relevance of this garment to our recommendation is how it uses a contextual trigger to extend the garment's expression (butterflies flying) to the environment.

Strategies for designers:

- Examine the specific use scenarios to find natural triggers for the interactions. Try to experience these contexts (Tomico & Wilde, 2015).
- Consider designing the impact of the garment's expression on the environment, on the wearer him/herself and/or on other people.
- One garment might be worn in multiple contexts, so consider changes in contextual conditions among them.

3. Control the Form of the Garments with Computational Materials

Using electronic components in traditional construction techniques to define the form of the garment can provide controlled changes within the fabric surfaces as well as overall silhouettes of the garment, which can lead to altered expressions on the form of the garment.

Traditionally, clothes can be designed either in a dynamic or static way. While some dresses may fit on a body and have a very limited dynamism, others can be designed to move by external effects such as wind. Still, these changes are usually spontaneous or even if not, they are hard to control. Our results suggest that by using computational materials to control the states of the traditional construction techniques, designers have a range of controls to make changes on surfaces or make full transformations for altering the garment's expression.

Design themes of *"Light on Surface"*, *"Dynamic surface treatments with computational materials"*, *"Weaving computational materials"*, and *"Changing the silhouettes of garments by controlling the fabrics with computational materials"* led us to create this recommendation. A good example of how changes can be controlled through controlling the appearance of the fabrics is Panic Run, in which the designers speculated on the pleats that were created with shape-changing materials. The computed pleats transform the silhouette and the patterns of the dress (Figure 5), while the transition process is also a part of the expression (i.e., how the pleats' speed can be controlled). In that direction, the Water Drop Bracelet exemplifies how continuous changes can be created in the patterns of the garment for creating dynamic expressions by scrutinizing the interaction between light sources and fabric surfaces (Figure 10).

As an external example, the shoulder pieces in Monarch (Hartman et al., 2015) are augmented via a muscle sensor, micro controllers, and servo-motors that alter its appearance based on the wearer's activation through holding their shoulders up. When activated, the pleats on the shoulder pieces quickly widen to create an altered silhouette as an extension of the wearer's expression (Figure 10). Also, the textile display created by Devendorf et al. (2016) is a good example of how computational materials can augment the expressive abilities of fabric surfaces. In this project, fibers that constructed the fabric surfaces were improved with thermochromic paint and conductive fibers by which they achieved visual patterns on the surface that are controllable via computation (Figure 10).

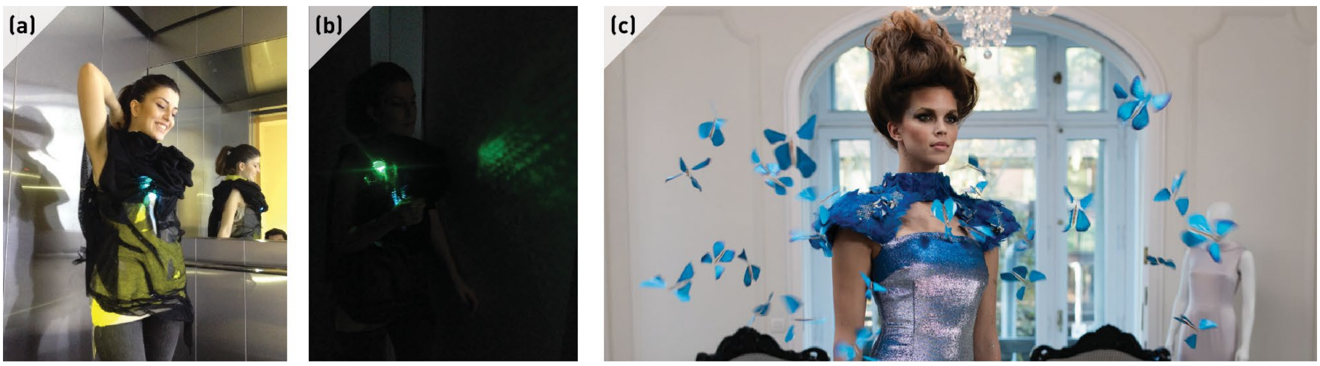

Figure 9. Examples for 2nd recommendation (a) Reflect the Night, activated LEDs via dance and music, (b) Reflect the Night, extended expression, (c) Butterfly Dress (Landau, 2014) with embellishments flying away.

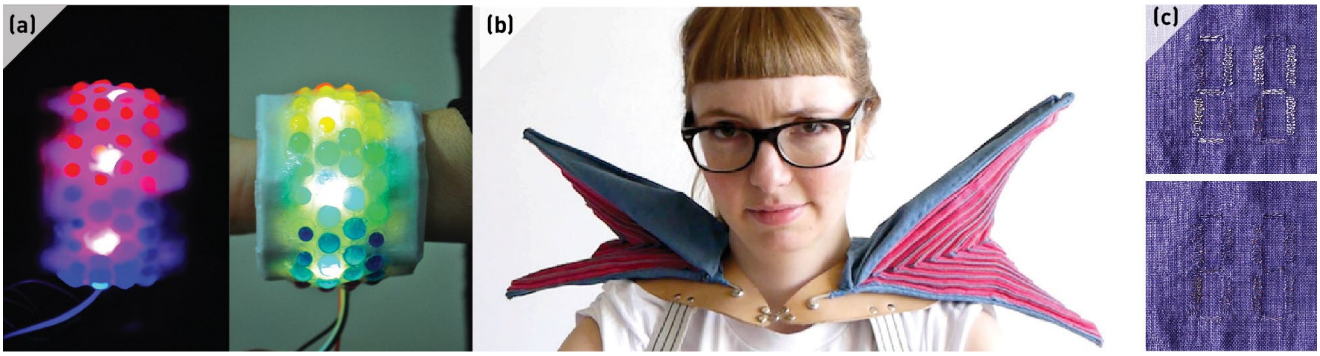

Figure 10. Examples for 3rd recommendation (a) Water Drop Bracelet, continuous changes in the patterns and interaction with light, (b) Monarch by Social Body Lab, OCAD University (Hartman, McConnell, Kourtoukov, Predko, & Colpitts-Campbell, 2015), altered the silhouette of the wearer via activated shoulder pads, (c) "Ebb" (Devendorf et al., 2016) textile display with computable patterns.

Strategies for designers:

- Explore the ways of controlling silhouettes and patterns of the garment via traditional fashion production techniques (i.e., controlling pleats, shape-changing materials in fabric structures, printing computable materials on fabrics).
- Consider and experiment on how computational materials will interact with fashion materials to alter their sensorial expressions when they are blended into clothing (i.e., how light creates effects on different fabrics, how firmness of the fabric reacts to shape changes).
- Keep in mind that transitions during state changes are also subject to expressions.
- Experiment with non-computed materials to see how alterations on the form might result before implementing computational materials.

4. Embellish Surfaces with Computational Materials

The computational materials can be applied onto fabric surfaces as an alternative way for traditional embellishments by defining their role in the overall composition of the garment or by creating new interactive embellishments by blending the material qualities of computational and fashion materials.

In fashion design, the physical form of the fabrics can be diversified through embellishment, such as by manipulating the surface (i.e., cutting holes) and/or by stitching on pieces (i.e., threads, pieces of fabrics, beads) that adds more depth to the surface. Our results suggest that the physical presence of electronic components on the garment can be used for embellishing the fabric surfaces or new computational composites can be designed to create dynamic embellishment effects on garments.

"Visible components on the garments" and *"Embellishing with computational materials"* were the design themes which helped us create this recommendation. A good example is Jellyfish since it speculates on the construction of new computational embellishments which alter the form of the fabric with its presence as well as by moving (see Figure 4). Also, Reform Season with its controllable cutouts (see Figure 6) is another example of computed embellishments on the fabric surfaces.

When it comes to external examples that represent subjects of this recommendation, Kino (Kao et al., 2017) is a good instance that shows how controllable embellishments can be designed to dynamically alter the fabrics' expression. In this project, the researchers explored how moving attachments on garments' surfaces might contribute to alterations in patterns or shape changes (Figure 11). Also, more and more electronic components are designed to provide aesthetics directly on garments. With its flower like look, the Lilypad Arduino processor board (Buechley, Eisenberg, & Catchen, 2008) and conductive threads embroidered on fabrics (Stern, 2008) are good examples of how these computational materials can contribute to the aesthetics of fashionable wearables by using them directly as embellishments on the garment (Figure 11).

Strategies for designers:

- Experiment with the decorational effect of electronic components by trying to use them as embellishments. However, this should not be considered as placing electronic chips etc. on the garment surface and drawing the design towards only cyborg-like style. What we mean here is to use or customize electronic components by considering its contribution to the overall form of the garment (i.e., incorporating weaving techniques or treating the cables as fibers).
- Think on ways of creating new controllable additions on fabrics that can behave as dynamic embellishments on the fabrics' surfaces.

5. Support the Three-Dimensional Shapes of the Garment via Computational Materials

The computational materials can be designed and used to create a structure for the fabrics to support the three-dimensional shape of the garments.

In fashion design, there are ways of altering the silhouette of the body by using additional structural elements to the fabric. For example, designers use plastic and metal internal structures on the fabric. The computational materials, which have usually hard and firm bodies, create an opportunity to use them for supporting the three-dimensional shape of the garments, instead of just hiding them on the garments. Results from our empirical study and discussions with experts highlighted that this can be achieved through improving the capabilities of the computational components, such as redesigning them to fit the exact needs of specific garment shapes (i.e., customizing the shape and the flexibility of the microprocessors), strengthening the fragility of these components, or designing custom supports with computation (i.e., producing supports with 3D printing).

"Using hard computational materials to create structures for the garment" design theme led us to form this recommendation. Still, it expanded into different methods such as 3D printing for creating the structure after receiving feedback from the experts. In our workshop, the example of using computational materials for supporting the shape of the fashion object was the Cable Bag. The designer of this piece specifically mentioned that, by using cables in the fabric structure, she was able to define an elastic shape for the bag which was not normally a case in wool bags (Figure 11).

Spider Dress (Kaplan, 2015) is a very good former example of how computational materials can inspire designers to create hard structures to change the silhouettes of a dress by creating materials with computation (Figure 11). Spider Dress can be seen as an extreme example and may not be fashionable as of yet, still it clearly exemplifies the opportunities.

Strategies for Designers

- Explore the ways by which and how the components of computational materials can support the fabric to contribute to the silhouette of the garments.
- Customize and create components for computational materials to support the three-dimensional structures of the garments.

General Discussions

The experts' positive feedback on the design recommendations indicated that engaging hands-on material explorations led to practical recommendations for fashionable wearables. The experts also mentioned that some of the aspects proposed in the recommendations matched their own practices, which might be used as a "reflective tool". They also highlighted that the recommendations are really valuable for educating novice designers and engineers in the field. This underlines the real value of our findings beyond this study. We can claim that by incorporating feedback from experts, which is a common method for deriving design knowledge (Mueller & Isbister, 2014; Sas, Whittaker, Dow, & Forlizzi, 2014; Zimmerman et al., 2007), we achieved clarity and applicability to our findings.

From a pedagogical point of view, based on our observations during the workshop, we can state that our workshop structure worked well towards the learning objectives we aimed. The first phase of the workshop aimed at enabling fashion students to understand the expressive potential of computational materials. In contrast to approaches which provide a set of inspirational pre-implemented samples prior to the design task (Perner-wilson et al., 2011; H. Profita et al., 2013), we presented raw computational materials to the students, and gave the open-ended task of designing art objects. As a response, the students not only explored new forms out of pre-defined material artefacts, but also repurposed the expressive uses of them. For instance, one student designer explored creating structures out of cables while another group of students started loosening the fabric structure of conductive fabrics. Moreover, the task of designing an art object enabled the students to focus on interactive expressions without concerning themselves with pragmatic functionalities. In the second phase, all but one of the groups of students transferred their expressions into the functional fashion object. For instance, one group worked with LEDs, positioning them between layers of fabrics to present an artwork illustrating the notion of dynamism, then used the same expression for a bicycle glow that assists a cyclist in navigating (see Figure 7). In this phase, the expressions they created reflected the functionalities as suggested by Hallnass and Redström (2002). Furthermore, throughout the process, we supported the designers with technical insights on the interactivity of the components.

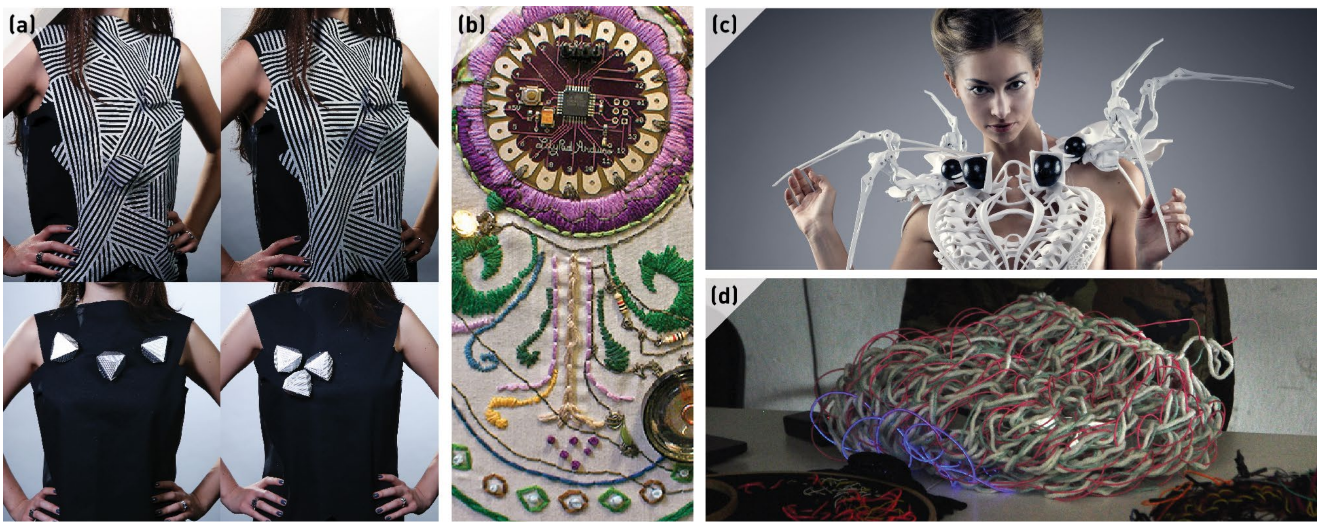

Figure 11. Examples of 4th and 5th Recommendation for 4th recommendation
(a) Kino (Kao et al., 2017) exemplifying pattern and shape change, (b) Lilypad Arduino used as an embellishment by Stern (2008), for 5th recommendation (c) Spider Dress (Kaplan, 2015) with 3D printed materials (d) Supported shape with knitted cables for Cable Bag.

However, we restricted the involvement of engineers in the ideation phase to prevent potential obtrusive effect of technical limitations. We observed that this restriction worked as the designers freely experimented with ideas and converged them into technologically feasible concepts with the help of the engineers. Yet, it should be noted that additional pedagogical treatments (i.e. design thinking exercises) might be taken to familiarize the engineering students with divergent inquiry, and eventually involve them in the ideation process. A similar approach has been applied in a semester-long interdisciplinary course by Martin, Kim, Forsyth, McNair, Coupey, and Dorsa (2013), in which it was found useful to include electronics prototyping, marketing, and user-centered design exercises in the course structure for enabling efficient interdisciplinary collaboration. Such interventions might result in design outcomes which push the boundaries of technology further.

We believe that our recommendations lead designers to explore theoretical notions of two disciplines in action. For instance, as also suggested by one of the experts, the first two recommendations might propose new approaches for the designers and researchers to seek embodied interactions (Dourish, 2001) on the body. By crafting the materials of fashion design with computational materials, designers can create wearables which allow the embodied meanings to be formed out of the intentional augmentation of what is already "physically manifested" on our bodies–clothing (see 1st recommendation). Also, the second recommendation directs designers to take the specific actions and multiple contexts of uses into account to define the interactions. This not only supports but also adds to the arguments of Tomico and Wilde (2016), as our results also direct the attention to changing contexts which are an important determinant of fashion behaviors of individuals (Giddens, 1991).

Furthermore, our recommendations reveal new exploration possibilities for the practical and the theoretical attributes of fashion (i.e., symbolic communication, constant need for change, and context dependency of fashion). For instance, with the recommendations on controlling the form of the garments (see 3rd recommendation) and embellishing fabric surfaces (see 4th recommendation) with computational materials, the designers were motivated to use dynamic and controllable ways of alterations on the expressions of these garments. We believe exploring these alterations might correspond to the different expressive needs (i.e., sporty, business) of different people and contexts in one garment, as well augmenting self-expressions with continuous dynamic changes on the garments. Although, such alterations in form of the garments practically exist in many wearable device examples, our work puts forth a detailed view on the subject by referring to the fashion techniques and terminologies and how those can incorporate the computational materials to create expressions. For example, while previous studies explored changing the overall form of a garment (Perovich, Mothersill, & Farah, 2013), our study suggests that designers can control the silhouettes of the garments via computational materials by borrowing terminology from fashion design for opening up new areas of investigations. Also, it broadens the previous knowledge by emphasizing that the transitions between these changing states are a concern of design, and the interaction between fashion (i.e., fabrics) and computational materials (i.e., LEDs, shape-changing fibers) should be considered (see 3rd recommendation). Moreover, proposing that the computational components can have both a sensorial effect on the aesthetic design of the garment with its physical presence (see 4th recommendation) and support the shapes of the garment (see 5th recommendation), and also provide a new perspective on these functional components that are usually neutralized or are hidden in the garments. By highlighting the importance of adapting them into the composition of garments with their physical presence, we did not direct designers to create critical wearables where showing these materials were motivated by ethical reasons (Ryan, 2016) or to hide their presence. Instead, we pointed to a direction where these materials could be blended and contribute to the expressions by describing examples. In addition, the 4th and 5th recommendations gave clues to being true to the computational materials. In the domain of architecture, being true means being honest in terms of material use (Farrelly, 2009). In the domain of fashionable wearables, or computational composites in general, being true to materials might lie in having an appreciation of all material qualities of the substrates in the expression. In that direction, our last two recommendations revealed how designers could exercise being true to electronics as well.

Conclusion, Limitations & Further Work

In this study, we examined the cross-pollination between fashion design and computational materials in the creation of fashionable wearables. First, we conducted a design workshop and analyzed the design process of seven projects to reveal what kind of expressive sources the interactive technologies might provide for fashion designers. The results of the analysis were presented as themes illustrating the expressive merger between fashion design and computational materials. Then, with the opinions of 10 international experts in related fields from different countries, we furthered these themes into 5 actionable recommendations for nonexpert fashion designers. This kind of systematic examination with the involvement of many different actors has not been carried out before. By providing this broader perspective in bridging two disciplines, we have revealed the design knowledge and actionable directions for supporting expressive explorations in wearable design processes.

We believe that designers can benefit from the recommendations in several ways since we do not only emphasize what might be the best practices but have also introduced *annotated portfolios* (W. Gaver, 2012) and different examples for applying them to different contexts and material combinations. These recommendations are beneficial as guides and inspiration points for fashion designers who want to introduce technological components to their designs but are unfamiliar with them. We also argue that, as also claimed by several different experts, being different from previous work, these recommendations are also useful for designers while discovering the possible outcomes of different combinations of fashion and computational materials in their existing designs. For instance, previous work has indicated that cloth can be an abstract way of ambient display (Jacobs & Worbin, 2005). However, our results suggest that criticality of information should be considered, and experimentation with the information regarding properties of cloth should be altered accordingly. Moreover, we also presented two distinct examples from our workshop: Jellyfish and Panic Run, which represent two end abstractions and directness in terms of giving information. We believe that the other recommendations are also informative in the same way for organizing and detailing the information fragments in the field.

In the present study, we provided a wide range of off-the-shelf computational materials as suggested by Vallgårda and Fernaeus (2015). Thus, the participants explored the fashionable wearables within the boundaries of these materials. We acknowledge that providing a broader range of sophisticated computational materials, such as living-bacteria based soft materials (Yao et al., 2016), might reveal more sophisticated computational composites and recommendations on more complex fashionable expressions. In this sense, the computational materials might have primed the emergence of the themes. Therefore, we are also curious to discover how these recommendations or design themes would change if we could introduce uncommon materials to designers. However, in a research through design process, another important aspect is to communicate the research process clearly so that the process can be replicated even if the results can not (Zimmerman et al., 2007). We observed that our pedagogical approach helped participants to design relying on the affordances of the material, without considering the technological restrictions. The process helped them to uncover expressions that lie behind the formal capabilities of these materials. We believe that similar studies can replicate our study to discover expressions beyond what we have proposed. Being aware of this restriction, in our interviews with experts, we facilitated the discussions more on design practices, processes, and outcomes to come up with recommendations which were independent from specific technologies. With the help of our interviews with experts, we expanded such simple themes into recommendations that do not target specific technologies.

Further follow-up studies can expand on our recommendations. For instance, as one expert commented on "embellishing fabrics with computational materials" by saying that such treatment methods achieved through detachable computational materials might create sustainable practices in wearable designs. Explorations on how the fabrics can incorporate computational materials to create recyclable material combinations can be valuable for sustainability in wearable designs. By considering those points, we intend to do more research through material explorations to reveal more knowledge on the contribution of computational materials to fashion design processes. Additionally, we want to realize the contribution of our recommendations by presenting them to designers and asking them to design wearables taking our recommendations into consideration.

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