Human Factors Considerations in the Design of Wearable Devices

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Wearable devices have great potential to support several application domains ranging from medical and safety critical, to leisure and entertainment. Wearable devices' solutions are promising, and extensive research has been conducted in this domain since the early 90's. However most of these works focuses on the feasibility of individual solutions. As such, the human aspects are often neglected, which can decrease not only the acceptance levels for novel devices, but also their sustained engagement. To facilitate the consideration of human factors in the early design stage, we present and define a list of 20 human-centered design principles. We explain how each principle can be incorporated during the design phase of the wearable device creation process. By adopting these principles, we expect practitioners to achieve better wearable solutions, improving the user acceptance, satisfaction and engagement for novel applications.

INTRODUCTION

Since the first sensors were produced, the wearable device field has evolved exponentially. This evolution not only applies to hardware through the miniaturization of technologies, the development of more efficient batteries and novel sensors, but also to where and how sensors are used. Wearable devices can be applied in several domains, ranging from entertainment to medicine and safety critical systems. With the sensors available today, wearable devices can monitor the vital signs of patients, augment human capabilities, replace and improve sensory organs, or even alert and intervene in medical emergencies.

Wearable devices have already proven to be successful in a variety of scenarios, however their problem space is wide and their design space is broad and largely unexplored (Suhonen, Müller, Rantala & Väänänen-vainio-mattila, 2012). The main challenges in this area concern human factors, including open issues as: how to properly fit the computer to the human in terms of interface, cognitive model, contextual awareness, and adaptation to tasks being performed. These are key areas for further research (Siewiorek, Smailagic & Starner, 2008).

For wearable devices and smart clothing to effectively interact with users, we must consider human aspects (Cho, 2010). To facilitate the consideration of human factors during design phases, in a more human-centered design approach, we identified a set of 20 human-centered principles that are relevant to orient designers during the design phase. These principles meet a general-purpose requirement, since they are applicable regardless of domain or use case scenario. They enable designers to effectively consider human factors during the wearable application design in the earliest stages.

This paper contextualizes the research domain in Section 1, summarizes related work, motivations and shortcomings in Section 2. Section 3 details the methodology followed, describes and applies the design principles. The contributions, and limitations of the solution proposed are reported in Section 4. We conclude in Section 5.

STATE-OF-THE-ART

Wearable computing is characterized by body-worn devices, such as clothing and accessories. By integrating computational capabilities, these devices are able to provide useful features to the end user. According to their applications and sensors, wearable devices can be found in different form factors, including but not limited to: armband (Jalaliniya & Pederson, 2012), anklet (Troshynski, Lee & Dourish, 2008), bracelet (Cheng, Griss, Davis, Li & You, 2013), contact lenses (Pandey, Liao, Lingley, Parviz, & Otis, 2009), necklace (pendant) (Gamboa, Silva & Silva, 2010), glasses (Kim, Yang, & Kim, 2012), gloves (Perng, Fisher, Hollar, Pister & Hall, 1999), jacket (Keng, Teh & Cheok, 2008), ring (Werner & Hornecker, 2008), shirt (Knight et al., 2004), shoes (Spelmezan, 2012) and watches (Atallah, Lo, King & Yang, 2010).

Wearable computing offers support and benefits and has already been applied to a wide range of scenarios: from safety critical domains, such as aircraft control, and medical applications (e.g. monitoring vital signs (Jalaliniya & Pederson, 2012), enabling accessible communication (Li et al., 2010), to entertainment, leisure (Keng, Teh & Cheok, 2008), gaming, and sports (e.g. snowboard training (Spelmezan, 2012)). Wearable devices enable monitoring, controlling, and tracking several human activities, and also provide solutions to end users when they have situation-induced impairments or disabilities. Low-cost wearable devices can be used to manage chronic health problems, prevent diseases, aid in early diagnosis, and continuously monitor a patient condition, significantly reducing her medical expenses (Hoof, Van & Penders, 2013), (Zheng et al., 2013).

The research in this field has been ongoing since the early 90's, but, due to the significant technological evolution after the year 2000, most applications date from the past decade.

The research efforts that have been done in the past decades in this field are extensive, but also constrained, since advances remain in individual fields (Cho, 2010) and most of them focuses on testing the feasibility of individual applications (Pandey, Liao, Lingley, Parviz, & Otis, 2009), (Li et al., 2010), (Cannan & Hu, 2011).

In a trial and error approach, a few studies have aimed at identifying design guidelines (Gemperle et al., 1998), (Siewiorek, Smailagic & Starner, 2008), providing insight into users' perspectives (Suhonen, Müller, Rantala & Väänänen-vainio-mattila, 2012), experiences (Troshynski, Lee & Dourish, 2008), or an overall assessment of wearable applications (Koch, 2009). Therefore, while it is possible to find extensive work on practicalities of wearable applications, there is no support to guide researchers to consider human-factors and their qualitative aspects during the design phase. By focusing on the feasibility of an individual approach, often usability and wearability are neglected. By excluding the users' perspective during the design phase, the devices' acceptance is likely to be compromised, especially when the resulting device is bulky, invasive or cumbersome (Angelini et al., 2013), and especially if recordings must be continuously made in their natural environments (Kidmose, Looney, Jochumsen & Mandic, 2013).

Besides this, the number of research findings that can aid designers to enhance the acceptability of wearables is very limited or very case specific (Tharion et al., 2007); and there is a lack of systematic knowledge (Karahanoglu & Erbug, 2011). From an industrial perspective, it has been noted that more than half of U.S. consumers who have owned an activity tracker (e.g wristband, smart watch), no longer use it (Figure 1). A third of U.S. consumers who have owned it stopped using the device within six months of receiving it. Adopting a human factors oriented strategy is the key to long-term success to ensure acceptance (Ledger & McCaffrey, 2014).

To contribute to the integration of human factors during early stage design of wearable applications, we first need to identify principles that are relevant for designing a human-centered wearable application, then we need to successfully incorporate these principles during the design phase, finally we need to assess their impact concerning users' acceptance, satisfaction and sustained engagement.

This paper lists, describes and discusses a set of 20 general-purpose human factors principles to be considered during the design of wearable devices. We illustrate the application of these principles with a case study.

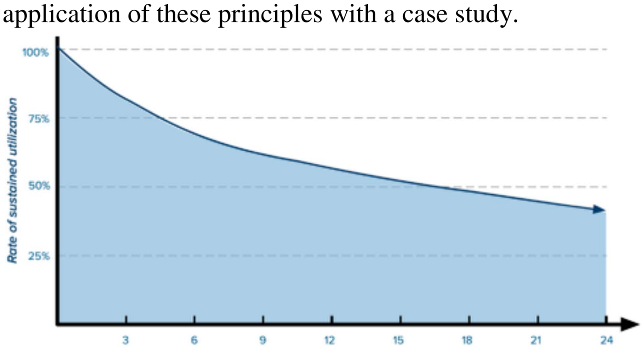

Figure 1. User engagement (percentage of use) vs. time (months) for activity trackers commercially available. [Source: Ledger & McCaffrey, 2014]

DESIGN PRINCIPLES FOR WEARABILITY

A design process involves a set of procedures of problem solving where various types of information are collected and synthesized to generate a consistent concept followed by a visual form (Cho, 2010). Given the inherent constraints of wearable devices, in this novel scenario the application of conventional principles of UI design is no longer valid. In the wearable context, contrary to a Desktop PC, interaction cannot rely on traditional interaction modalities, and both input and output approaches must be re-imagined and re-designed. The design alternatives are more limited in terms of device dimension, and the interaction contexts are more varied, being characterized by dynamic environments, users on the move, and more specific target audiences (elderly user, children, adolescents).

To guide design decisions towards human-centered aspects, we identified 20 key principles that have been recurrently highlighted by various experts in the wearable domain. These principles involve factors that are relevant and should be considered during the design of wearable applications. They aim at meeting users' requirements, achieving higher acceptance levels, and sustaining engagement. To identify these principles, a systematic literature review was performed, involving more than 1,000 scientific articles that include as keywords ('wearable device' and 18 form factors: "anklet", "armband", "belt", "bra", "bracelet", "contact lenses", "chest mounted", "earring", "earpiece", "glasses", "glove", "headphone", "head mounted", "necklace", "ring", "shirt", "shoe" and "watch"). Digital libraries of ACM DL, IEEEXplore, Springer and Google Scholar have been used. The search has been conducted in the first trimester of 2014. We searched for human-centered principles and quality factors that could influence the end user acceptance and engagement with wearables.

The 20 wearability principles identified with the systematic literature review involve both hardware and software aspects of devices. They are defined as follows:

P1) Aesthetics. Concerns aspects of the form and function of any wearable object (Gemperle et al., 1998), mainly associated with its attractiveness level. An attractive design, rather than a medical one, tends to improve the desirability of a device (Angelini et al., 2013).

P2) Affordance. Concerns the level of intuitiveness of a device in physical aspects of the interaction and their interpretations (Svanæs, D., 2013). It respects the shape of the human body and its anatomical constraints.

P3) Comfort. Concerns the freedom from discomfort and pain (Cho, 2010). Users feeling enough *comfort*, no longer sense the device after some time wearing it. Comfort involves an acceptable temperature, texture, shape, weight, and tightness (Tharion et al., 2007). Comfortable devices fit users enabling normal movements, without constraints (physical or psychological). Flexible materials for instance, permit normal joint movements (Knight et al., 2004). Smaller form factors and more convenient sensor locations on the body can aid to ensure comfort (Hoof, Van & Penders, 2013).

P4) Contextual-awareness. The scenarios in which the wearable device will be used must be clearly understood and considered during the design process. The comfort perceived by users is strongly affected by the device purposes (Siewiorek, Smailagic & Starner, 2008), varying significantly depending on social contexts. Understanding well the context is a key factor in the design process, as device's properties can be affected, for instance by cultural differences (Karahanoglu & Erbug, 2011). They are essential criteria to consider and to reach users' acceptance.

P5) Customization. Humans considerably vary in shape, size and dimension, and also in their preferences, interests, and wishes. To engage users, the look and feel of the wearable devices should enable customization, considering varied aspects, as the users' sensitivities, wishes and interests (Boujarwah, Sadler, Mogus, Abowd, & Arriaga, 2010). Customization in size, color and appearance aids users to feel more comfortable wearing the device and to integrate it to their normal outfit (Hanson & Ljungstrand, 2000). Personalized options include: colors, functions and weights and sizes (Angelini et al., 2013).

P6) Ease of Use. A straightforward, simple and intuitive interface (Siewiorek, Smailagic & Starner, 2008) enhances the usability levels of the device, aiding to increase the engagement levels of users. Both input and output interfaces should be easy to use (Cho, 2010).

P7) Ergonomy. Refers to the physical shape of the device, its ergonomic aspects regarding the respect to the body anatomy, its constraints and how users perceive it (Lin & Kreifeldt, 2001), (Baber et al., 1999).

P8) Fashion. Can strongly affect the perception of comfort and desirability of a wearable device (Siewiorek, Smailagic & Starner, 2008). It refers to how stylish the technology is, helping to make the device more (or less) ubiquitous, integrating it in to a conventional landscape.

P9) Intuitiveness. Concerns the immediate understanding of how the interaction occurs, e.g. regarding existing buttons, keys, commands, and features (Siewiorek, Smailagic & Starner, 2008). It applies the affordance concept to the cognitive aspects of the interaction.

P10) Obtrusiveness. Physiological sensors have various degrees of intrusiveness, where intrusion may involve using body tissue to diagnose a particular physiological state or condition. Devices said non-intrusive are often obtrusive and cumbersome to some extent. Devices should be transparent (Oliver, Sinclair, & Tan, 2007), enabling natural body movements (Knight et al., 2004) and carefully considering anatomical characteristics and constraints of the human body.

P11) Overload. Differently than technology, that has been facing a continuous miniaturization process, humans still have a finite and limited processing capacity. Thus the number of concurrent activities they can perform is limited, posing a special challenge to designers of wearable devices. Mobile interfaces may hinder the user's primary task if they do not properly consider the human cognitive capabilities during the design process (Siewiorek, Smailagic & Starner, 2008).

P12) Privacy. Refers how subtle the interaction can be, i.e. how discreetly is possible to exchange information, for input and output, and mainly when users need confidentiality ensured. Exclusive communication channels can ensure privacy and discretion (Lee & Lim, 2011). Users must be able to choose their desired level of privacy in parts of or in all collected data with respect to access by users' groups (e.g. relatives, friends, and practitioners) (Oliver, Sinclair & Tan, 2007).

P13) Reliability. Refers to the level of confidence and trust that users have on the device (Cho, 2010), concerns safety (no harm to the user), precision (provide faithful, accurate data), and effectiveness (expected responses).

P14) Resistance. Understanding the context in which the wearable device is used, aids practitioners to identify acceptable levels of resistance, specially considering: abrasion, impact, temperature, humidity, flexure and laundering. Devices should resist washing and wearing (Cho, 2010), ensuring durability (Tharion et al., 2007).

P15) Responsiveness. Users tend to be less patient when they are on the move than when at a desktop, as such it is important to provide them feedback in near real time, ensuring high levels of system responsiveness (Siewiorek, Smailagic & Starner, 2008). Ensuring high responsiveness helps users to complete their tasks more efficiently and productively (Cho, 2010).

P16) Satisfaction. Concerns how the device is able to meet users' expectations, wishes and requirements. It involves varied aspects, e.g. effectiveness, performance, and beauty. It measures the overall level of fulfillment of users emotionally and functionally (Cho, 2010).

P17) Simplicity. Refers to the ease of use, intuitiveness and affordance of the device, i.e. by putting simple interaction options and by presenting the feedback needed in a simple manner, the user can interact in a straightforward manner, with more efficiency (Siewiorek, Smailagic & Starner, 2008). It respects principles of a minimalistic design by including only features and interaction options that are fundamental to accomplish available tasks.

P18) Subtlety. Refers to how transparent the communication is, e.g. notifications intended for the owner of the device, should not disturb other people nearby. Notifications should not be a social issue (Hanson & Ljungstrand, 2000). Users are often concerned with excessively attracting other people's attention (Lee & Lim, 2011); a subtle approach ensures more privacy and discretion to users.

P19) User friendliness. Respects the mental model of the end user, proposing options that facilitate the interaction, in an easy and intuitive approach. In case of errors, recovery should be made available (Cho, 2010).

P20) Wearability. Considers the physical shape of objects and their active relationship with the human form (Siewiorek, Smailagic & Starner, 2008). Wearability includes most of the principles previously defined (Tao, 2001), as comfort, affordance, and aesthetics. It is a key factor for the success of a device, in terms of user's engagement and satisfaction. 'Dynamic wearability' occurs when the devices is worn with the body in motion (Gemperle et al., 1998).

Application

To illustrate the application of the principles we selected and applied 6 of them in a study. This study compares to which extent 4 interaction modalities common to wearable devices (audio, graphic, tactile, and haptic), impact 6 principles (discretion, privacy, obtrusiveness, cognitive overload, ease of use, and intuitiveness). A 3-point scale was used, where 0 is the lowest evaluation (e.g. not intuitive at all) and 3 the highest (e.g. highly intuitive).

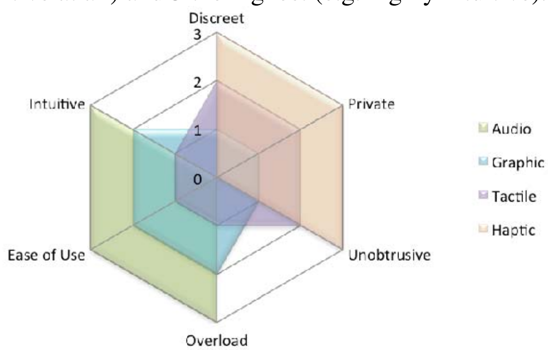

Figure 2. Comparison of 4 interaction modalities (audio, graphic, tactile and haptic) for 6 wearability principles (discretion, privacy, unobtrusiveness, overload, ease of use, and intuitiveness) in a 3-points scale.

This analysis follows an empirical reasoning, i.e. it is logical that audio interaction is more intuitive, easy to use (familiar) but causes a higher cognitive load requiring constant attention of the user (Spelmezan, 2012). The haptic modality, on the other hand, ensures more discretion, privacy and unobtrusiveness. It also requires less cognitive load, but it is not so easy to use or intuitive, since users are not used to it (Lee & Lim, 2011). Observing Figure 2, we note that the graphic and tactile modalities provide a better balance among the 6 principles chosen for analysis. This example illustrates that a radar chart can be effectively employed for graphical visualization of principles' analysis, enabling comparison of devices, models, brands or evaluation scores from different groups of users. In this example (Figure 2), a Likert scale with semantic differential of 3 points has been employed associated with respective scores; more extensive scales can also be applied though. Although more principles can be included, a set of 6 has been chosen ensuring legibility.

DISCUSSION

Among the principles proposed, some present strong correlations, e.g. *Affordance* and *Comfort*. By certifying that the body shape, size and constraints are properly considered in the design process, a more comfortable device can be produced. *Ease of Use*, *Intuitiveness* and *User friendliness* are also strongly correlated, i.e. an intuitive interface tends to be easier to use and consequently more user friendly. Other principles have a negative correlation, leading to potential trade-offs, e.g. *customization* and *simplicity*, mainly because by allowing users to choose the characteristics of their device, more complexities, as additional features, need to be included in the interfaces.

Other complementary principles are also relevant for the wearable design process, however they have not been added in the list of principles since we mainly focused our search on human-centered aspects. These complementary principles are often strongly related to practitioners' perspective, be it medical or technological. They include:

Accuracy. Many sensors have been launched in the past decades, and although their effectiveness has been proved, their accuracy levels can significantly vary. Medical and safety critical applications require more accuracy of sensors. These contexts imply high-accuracy levels, high reliability levels and prompt responses (Oliver, Sinclair & Tan, 2007). The error tolerance must be properly identified according to each specific application.

Availability. The sensors for continuous monitoring of vital signs must present constant availability. To ensure it, the battery levels and power consumption are critical aspects to be continuously monitored.

Safety. Refers to any type of harm (physical, social, psychological), avoid problems as overheating or electric shock. Safe devices consider their physical forms, electromagnetic waves, electricity, etc. (Cho, 2010). Still, the long-term use of wearable devices has unknown physiological effects on a human body (Gemperle et al., 1998).

Security. Refers to the overall aspects for a secure device, concerning for instance, confidentiality, integrity, accountability, and privacy as well. Security involves data collection, storage, transmission and communication.

Due to its multidisciplinary genre, making the best design decisions for wearable devices is a challenge. It is hard to simultaneously consider and properly prioritize perspectives from users, technology and medicine. Considering their specific requirements and constraints can lead to many trade-offs, e.g. while from the users' perspective, aesthetics and comfort is mandatory; from a technological perspective, functionality and battery life are priorities. From a medical perspective, accuracy and availability are essential. Dealing with these multidisciplinary priorities raises discussions in the design process. Thus, practitioners must carefully analyze the costs and benefits of each solution before making proper decisions.

To assist in bringing human factors aspects into the design phase, this paper defines 20 human-centered principles that can guide designers through the design process centering their solutions in users' wishes, interests and requirements. These principles can pave the way for designers to focus on human factors during the development of novel wearables. Still this process is complex, being case specific and context sensitive. Thus, although principles may guide design decisions, to effectively satisfy users, potential trade-offs must be also carefully analyzed. Trade-offs include: technical and ergonomic requirements (Knight et al., 2004), available features vs. device size, and computational power vs. battery life (Angelini et al., 2013). Practitioners must also have a clear understanding of target users and their contexts (characteristics, specificities and constraints). User centered approaches have been proved useful in this process, alternating iterations and evaluations, such as focus groups, interviews and surveys.

CONCLUSION

Moving beyond a conventional desktop interface makes the design process more complex, environments are multivariable and dynamic, impose new constraints that existing theories cannot fully support. Simply shrinking down computing tools from the desktop to more portable scales leads to mini PC's, ignoring opportunities of a new context, and excluding the human as source of context (Gemperle et al., 1998). Better defining wearability can raise designers' awareness to treat its requirements as concretely as technological ones, matching those to users' requirements early in the design (Gemperle et al., 1998).

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