Psychophysical Elements of Wearability

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ABSTRACT

Wearable technology presents a wealth of new HCI issues. In particular, this paper addresses the impact of the physical interaction between the user's body and the device's physical form on the user's mental representation of self and cognitive abilities, a blend of HCI and ergonomics that is unique to wearable computing. We explore the human sensory mechanisms that facilitate perception of worn objects and the elements of sensation that influence the comfort of worn objects, and discuss the psychological elements that may cause worn objects to be forgotten or detected, wearable or not. We discuss the implications of un-wearability on attention and cognitive capability.

Author Keywords

Psychophysics, wearable technology, wearable computing, wearability.

ACM Classification Keywords

H.1.2 User/Machine Systems: Ergonomics.

INTRODUCTION

The concept of 'wearability' is an important theme in wearable computing. In this context, we use *wearability* to refer to the degree of comfort (physical, mental, emotional, and social) afforded by a body-mounted object or device, rather than the possibility of it being mounted on the body. Wearability is essential to the function of wearable devices for many reasons: most importantly, a device that is "unwearable" (meaning in this context that it causes discomfort or is difficult to wear, not that it is impossible to mount on the body) simply will not be adopted by its user. There are numerous examples of this behavior in studies of protective clothing: garments that are uncomfortable or even just considered unattractive by users will simply not be worn, or will be worn in a modified way, even if this means putting the user's life in jeopardy. Although there is no one commonly-accepted definition, degree of wearability is generally accepted to be affected most by the interaction between the wearer's body and the physical form of the worn device, the ergonomics of a body-mounted object. Because of the immense scope of use scenarios and inherent interdisciplinarity of wearable technology, the contributing factors of wearability are complex and difficult to itemize. In this work we will focus not on the physical manifestation of comfort or discomfort (body temperature, muscle fatigue, etc.), but rather explore the cognitive and psychological experience of wearability: the ways in which the user's sensory faculties perceive and model the worn device. We will then present a new implication of wearability: it's interaction with HCI, or the impact of perception of the worn device on the user's cognitive capabilities.

BACKGROUND

Although it is recognized as having a distinct impact on the function of a device, wearability itself has undergone minimal study. Gemperle et al. [8] conducted the most comprehensive study specifically concerned with wearability of technology. In that work, researchers developed body-mounted shapes intended to determine the amount and location of available body real estate. To determine these shapes, volume and curvature data were taken from a variety of subjects and used to inform the shaping and location of body-mounted pods. These pods were then refined and integrated into an extensible textile housing, and the comfort of the pods evaluated by subjects during movement tasks. Their research outlines important design criteria for wearability based on their experience in wearables design, and describes the shape and location of optimal sites for body-mounted electronics without reference to specific applications, device functionality, or use scenarios.

Our previous work [5] also outlines variables important to wearable comfort, including thermal and moisture management, flexibility, mobility, and durability, with an extra emphasis on sizing and fit and its relation to wearability and device performance. Similarly, McCann et al. [12] describe several important human-factors variables for consideration in the wearable design process.

Most prior wearability research specifically devoted to wearable technology has focused either on defining the size and shape limits of technological components, or on itemizing or measuring the variables involved in wearability. In this work, we seek to discuss the mental mechanisms of wearability by exploring the junction of physical sensation and psychological representations of self, towards the determination of the elements that allow a worn object to be perceived as part of the body itself, rather than a distinct entity.

CUTANEOUS SENSATION

There are seven major types of mechanoreceptors in the skin, which cooperate to generate impulses perceived as various forms of touch. These types are outlined in Table 1.

Receptor Type	Sensation
Meissner Corpuscle	Stroking, fluttering
Pacinian Corpuscle	Vibration
Merkel Disc	Pressure, texture
Ruffini Ending	Skin stretch
Hair tylotrich, Hair guard	Stroking, fluttering
Hair-down	Light stroking

Table 1: Mechanoreceptors of the Skin

The first four types in Table 1 are present in all skin, the last two only in hairy skin. The types differ based on their rate of adaptation: Meissner and Pacinian Corpuscles are rapidly-adapting, meaning they return to their resting state quickly after receiving an impulse, whereas Merkel Discs and Ruffini Endings are slowly-adapting, meaning they remain responsive for a longer period after experiencing a change [14]. However, all receptors eventually return to their resting state—this means that a constant, perfectly static stimulus (like pressure, for instance), will cease to be felt as long as it does not cause pain.

These receptors facilitate the sense of touch, and allow the skin to sense stroking, fluttering, pressure, vibration, and skin stretch. To this are added the other sensations related to cutaneous sensing: temperature and pain (believed to be involved with, but not belonging to, the sense of touch). Pain is detected by unmyelinated nerve endings in the skin, and temperature, while not completely understood, is believed to be detected by the same nerve endings.

We can see from looking at the things skin can sense (and, of course, from personal experience) the elements of skin sensation, the major component of detecting worn objects.

ELEMENTS OF CLOTHING COMFORT

To put this cutaneous sensation information in the context of clothing comfort, it is necessary to compare the elements of sensation with the common elements of clothing comfort. Wearable technology does not always take the form of a conventional garment: many wearable devices are mounted on or suspended from the body in a manner similar to a bag, belt, or accessory. However, the elements of comfort that apply to garment-integrated technology incorporate those of most body-mounted technology (while the inverse is not necessarily true), so we will concern ourselves here with the elements of clothing comfort.

Clothing comfort is generally believed to be influenced by the following factors:

- Pressure/Constriction
- Texture
- Thermal balance
- Moisture transport
- Freedom of movement

Of these, the first three are directly related to skin sensation modalities. **Pressure** and **constriction** can be experienced in three dimensions: as a point of pressure (where force of a mass on the body is focused at one point, such as a digging corner of a solid form), as a line or band of pressure (a digging edge or belt), or as a planar pressure (such as a circumferential compressive garment like a girdle, or as force spread over a contoured surface). **Texture** is generally not felt statically (unless the force is great enough, in which case it is experienced as an array of pressures), but rather as the movement of tactile stimulators over the skin. The intensity and quality of the dynamic stimulus is experienced as texture, which may resemble stroking or fluttering, scratching, or even pain. **Thermal balance** is detected by heat and cold receptors in the skin, and can be affected by external temperatures as well as the generation of body heat. **Moisture transport**, a significant and often studied element of clothing comfort, is not directly detected by the skin. Rather, it is detected as a combination of mechanical stimulation and thermal change. External moisture may strike the skin with a detectable force, and/or affect the texture and movement of other surfaces over the skin. These factors, in combination with the thermal changes experienced due to conductive heat transfer, are experienced as wetness.

Freedom of movement, the last factor, is the most complex sensed factor of the above list. At the skin level, it is most often experienced as a pressure force (generally linear or planar) which impedes or halts the generated body movement. It is also felt as a compressive force that is experienced during movement (but does not necessarily impede that movement), or as its corollaries, the experience of increased temperature or moisture due to increased muscular effort.

Traditional clothing is generally primarily composed of textile elements, with small metallic or plastic additions such as embellishments, zippers, buttons, or other fasteners. Wearable technology, on the other hand, generally has a much higher concentration of metallic or plastic elements. It is these elements that most often result in a tactile distinction between “standard” clothing and wearable technology. Technological components are stiffer and heavier than most elements of standard clothing. Integrated into clothing, they can create swinging masses or digging edges, which in turn result in discomfort. Sensors that require skin contact can cause moisture build-up, scratchy surfaces, or small hard areas in contact with the skin. Heavy weights supported by weaker muscles (such as on the forearms) can result in restricted movement and fatigue.

How, then, do certain worn objects like wristwatches disappear so seamlessly from consciousness, where others fail?

BODY SCHEMA AND PERIPERSONAL SPACE

Psychologically, humans generate a dynamic understanding of the size, shape, and physics of their bodies. This understanding is known as "body schema" [9], and it allows us to navigate physical spaces and manipulate objects. The space designated as part of the body schema is surrounded by a spatial area known as peripersonal space. Peripersonal space is generally differentiated from extrapersonal space by our reach abilities. Objects that can be reached without locomotion are within peripersonal space, objects out of grasping distance are in extrapersonal space [16].

It would seem logical that the body schema incorporates the body itself, but interestingly our notion of body space can be temporarily or permanently extended to include things like tools or prosthetics. This is shown in subjects with selectively impaired cognitive function: patients who have difficulty manipulating objects in peripersonal space also have difficulty manipulating objects in extrapersonal space using a physical tool, but not when using a laser pointer [4]. Visual receptive fields that generally encompass only peripersonal space are extended to include the space reachable by a physical tool [10]. Extensive research has been conducted in the exploration of the impact of tool use on extending peripersonal space, resulting in the conclusion that tool use extends the perceived peripersonal space to include the reach of a tool, and that this extended perception lingers for a short time following tool use [11]. However in many of these studies, no specific distinction is drawn between body schema and peripersonal space. Because of the nature of the task (generally using a tool to complete an action, or responding to a visual stimulus presented near or on the far end of the tool), it is difficult to definitively decide whether or not the tool has been incorporated into the body schema itself, versus whether or not peripersonal (or grasp-able) space has been extended to include the length of the tool. Experiences of amputees with phantom-limb sensation support the notion of a dynamic body schema. Following amputation, many patients experience sensation or pain that seems to come from the missing limb. Over time, this sensation telescopes in upon the stump, but attachment of a prosthetic can alleviate pain and restore that part of the body schema [13].

The fine distinction between body schema and peripersonal space has theoretically been drawn in terms of consciousness. The body schema is postulated to be an unconscious representation of the body, whereas peripersonal space is generally considered to be a spatial area that is interacted with consciously (NB, that is not to say that it is always *voluntarily* interacted with: take the common example of an object entering peripersonal space at some velocity, resulting in a startle response).

DEFINING BODY SCHEMA THROUGH ATTENTION

If the line between body schema and peripersonal space is drawn at the borders of consciousness, it follows that an object (garment, device, etc) that is mounted on the body will be removed from the body schema at the point at which it demands unusual attention from the wearer. Thus, this definition is closely tied to the definition of wearability: a perfectly wearable device is instantly integrated into the body schema, and remains such part until it is removed from the body. A very unwearable device is continually surprising to the wearer, constantly demanding attention and interrupting cognitive processes.

It is important to note here that human adaptability is such that almost any intrusion, short of extreme pain, can be adapted to. Thus, with enough incentive, a user will become accustomed to the most poorly designed of wearable devices. One has only to look at the history of prosthetics and medical devices to be convinced of this. In this context, however, we are concerned with a shorter timeline of adaptation, and a lower threshold of acceptability. The everyday user of non-life-saving wearable technology will simply abandon a poorly designed device, long before s/he has used it for long enough to become accustomed to it.

Adaptation to a worn device involves the progressive decrease in attention paid to tactile sensation caused by the device. There are three levels of sensory stimuli: stimuli that are attended to and processed, stimuli that are not attended to but subconsciously processed, and stimuli that are not attended to and not processed [6]. In the last category of unattended stimuli, sensory receptors actually cease to react: this category is limited to continuous impulses, impulses like continuous pressure where the slowly-adapting pressure receptor (Merkel Disc) returns to its resting state, or where the reaction time of a rapidly-adapting Pacinian Corpuscle cannot keep up with the rate of vibratory input. Unattended but subconsciously processed stimuli stimulate sensory receptors, and may even generate a response, but may not be consciously processed by the brain and thus are not stored in memory. When asked, a subject will not remember the content or quality of the stimulus. Subconscious processing is what allows us to suddenly attend to a previously unattended stimulus, such as when we overhear our own name in an adjacent conversation. Attended stimuli are processed and stored in either short or long term memory.

Attending to sensory stimuli may even increase the receptor response. For instance, studies have shown that attending to a pain response increases the neural activity in the brain, and the pain response itself. When a subject is distracted, the pain response actually decreases [1].

There are numerous examples of the cognitive effects of cross-modal distractor stimuli [6]. Anecdotally, we can all recognize the impact of a sensory distraction on our cognitive flow. In writing this paragraph, for instance, I was interrupted by a particularly bad smell, which required that I shift my attention from writing to determine the source of the stimulus, and subsequently leave the desk and close the window. So it follows logically that the point at which the physical sensation of wearing an object passes from the category of unattended stimulus into attended stimulus in an involuntary manner is the point at which an object becomes dissociated from the body schema. The causes for this attentional demand can then be traced back to the sensory capabilities of the body. We have discussed the various stimuli that cause sensory response, but why then are not all stimuli attended to? This is likely due to their predictability and magnitude. An unpredictable or unusual stimulus requires attention, as does an unpredictably or unusually large stimulus. Over time, the mind learns which stimuli are normal and expected, and these cease to be attended to. Again, any regular stimulus short of extreme pain can eventually fall into this category, as the brain is capable of subconsciously learning very complex patterns. However, we are concerned with minimizing the adaptation threshold.

WEARABILITY AND COGNITION

If un-wearability is hypothesized then to cause involuntary shifts in attention, it can then be assumed to have a negative effect on cognition. Indeed, several studies have indicated such an effect. Bell et al. [2] tested the impact of textile comfort on the cognitive performance of US soldiers, and found more abrasive textiles resulted in lower response accuracy and longer response time. In a field experiment, Bell et al. [3] tested graduate students taking a statistics exam. Of the variables studied, only two, clothing comfort and confidence in taking the exam, showed significant correlation with exam performance. Surprisingly, clothing comfort was the stronger correlation at 0.64, compared with 0.46 for confidence. (NB: it is difficult to claim causality in such a study, see reference for the authors' extensive discussion of influencing variables.) In earlier work, Fine [7] found that heat stress led to a decline in cognitive performance among soldiers wearing chemical protective equipment, and Rauch et al. [15] found a decline due solely to the chemical protective equipment (although there is some question, especially in [15], of the role that decreased manual dexterity and visual acuity played in that decline).

None of these experiments tests explicitly the intrusion of wear discomfort into conscious attention. Unfortunately, no such explicit investigation has been conducted to date, perhaps due to the difficulty of explicitly measuring this type of distraction.

CONCLUSION

We hypothesize here that wearability can be described psychophysically as the degree to which sensory stimuli generated by a worn object intrude into the wearer's conscious attention, and we suggest that this intrusion has cognitive consequences for the wearer. Wearable technology is most often designed to be a cognitive aid to the user: either by explicitly providing information to the user, or by gathering context information about the user, which is then used to inform the operation of other cognitive aids (such as personal or ambient computing devices). Thus, wearability can be seen as essential both to the willingness of the user to accept and use a wearable device, and to the ability of the device to actually provide a cognitive aid. Wearability therefore becomes an essential part of the human-computer interface.

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