Putting Haptics into the Ambience

Karon E. MacLean, *Senior Member*, *IEEE*

Abstract—In an attentionally overloaded world, relief will come only from interfaces between humans and computation that are able to provide information in the background of our sensory and cognitive processes. Haptic displays may have a special role to play in this emerging movement toward *ambient interfaces*, because the touch sense is well suited to present many types of information in a way that treads lightly on our mental resources. This paper offers an introduction to the notion of ambient information display, and explores why and how the haptic channel could contribute. It begins with a discussion of the attentional problems posed by contemporary interface technology, and a broad overview of ambient interfaces themselves: their purpose, specification, features, and some general examples. Sense is made of the *haptic* ambient design space through a morphology of the functionality and social configurations exhibited by existing and envisioned examples. Finally, reflections on design principles and challenges for ambient haptic interfaces are aimed at inspiring, shaping, and informing future development in this area.

Index Terms—Haptic I/O, human computer interaction (HCI), human information processing, ambient interfaces.

1 Introduction

In the beginning there was a computer, and the people around it served it, and to do so they learned its language.

The computer could soon do many things better than humans. Its designers began trying to make it speak *their* language. A dialogue between computer and user developed: the user issued commands, the computer responded ... as well as it could, we must assume, as much as sometimes it seemed to misunderstand on purpose.

In time, the computer became very small and very smart. Its smallness allowed it to spawn and spread. Its many selves appeared in automobile navigation, missile guidance and building access systems, cell phones, vending machines, clothing, refrigerator doors, pop cans, and singing greeting cards. These selves could talk to one another over networks and guess many things about where their users were, what they wanted, and what they intended to do to "help" him or her. Sometimes, the guesses were right.

Since most people had not yet evolved internal Bluetooth or WiFi receptors or had them implanted, the computer was forced to use the same primevally slow and stubbornly unevolving communication channels as always: peoples' eyes and ears. Graphical displays got smaller, and smaller still. City streets, buildings, parks, and cars filled with vacant-eyed zombies with inner selves focused on earbuds attached to music players and cell phones.

The computer began to use the increasingly detailed information it collected to (always helpfully) *initiate* communication with its user. It reminded, notified, and asked her about things she needed to know (that an email has arrived, for example, and perhaps she'd like to read it instead of writing this paper), or wondered if it should do for her (like upgrade the word processor to a new, improved version just before said paper was due). The computer wasn't good at guessing when or how to interrupt and had limited options for getting inside her brain to prepare her for an intrusion. These interruptions really interrupted.

Eventually, the humans spent almost all their time noticing the computer's suggestions, answering its questions, or else endlessly talking and writing to each other in the new profusion of time, place, and media that the computer made possible. It was sometimes entertaining, often engaging, and certainly kept them busy. But the humans started wondering who was really running things, and whether all the fun was getting in the way of real thinking and doing.

The computer could communicate now, in a way; but what about a bit of social intelligence?

1.1 Ambient Computing and Haptics

The ubiquity of networked information today and the communication technologies that accompany it bring many opportunities; but humans are limited in how and how much information they can process. Today's computer-supported environments fail to recognize these constraints in basic ways, even when functioning as intended. The result is an emergent cultural pastime of human interrupt handling. It has some unfortunate effects, arising from both information overload and from the jarring and discontinuous way in which information comes to us.

The overload problem will be solved by information and communications triage and filtering. Meanwhile, appropriate information *display* has emerged as a major objective of computer-human interaction (CHI) research and industry development. Context-aware, pervasive, ubiquitous, and affective computing subdisciplines have strong ties to the study of attention, perception, cognition, and emotion.

Enter *ambient computing*. Ambience means "existing or present on all sides: encompassing" (Webster). In this vein, some basic premises underlie this approach to humanizing the information fire-hose. One is that a user's context should determine interruptibility [1], [2]. Sensor-based systems able to do this are in early stages of development [3]. Another is

• The author is with the Department of Computer Science, University of British Columbia, 2366 Main Mall, Vancouver, BC V6T 1Z4, Canada. E-mail: maclean@cs.ubc.ca.

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the idea of attentional *center* and *periphery* introduced by Weiser and Brown in the early 1990s [4], [5]. Relevant but not-yet-critical information should live in the user's peripheral attention in an undistracting but accessible way, ready to move "calmly" into the center at the right time.

What do haptic interfaces have to do with ambience? The haptic sense[1] is well posed to present background, ambient information. It is how sighted people generally use touch in the physical world: even when the information it provides is essential to a task at hand (the friction between paper and pen, the weight of the surgical knife and the elasticity and toughness of the tissue it will cut, and the fullness and heat of a coffee mug), touch is usually a supporting player rather than an explicit focus. The tendency of current technology to channel information through the graphical display overwhelms vision, and commits the further error of dropping this rich and vital background channel.

The following discussion begins by examining the motivation for and principles of ambient interfaces, and illustrating them with some seminal visions of how they might work. It proceeds to see how existing *haptic* examples can be organized into a morphology of social configuration and intimacy, and concludes by outlining key design principles and challenges.

2 When Information Isn't Ambient

Discontinuities in information and communication transmission manifest as contention for a user's attention. They occur in *awareness, transitions* from background to foreground, and *switching* between different resource-demanding tasks.

2.1 Awareness

In a more mechanical world, there is often a low-level visibility and presence of the machines supporting our activities. An engine's laboring gives clues to its load, which can be felt and heard. A bumpy road is communicated through the steering wheel and seat. With computing machines, indications of effort or errors tend to be indirect and obscured. Responsiveness of other applications diminishes, or the computer crashes. Exceptions are usually unintended: the fan in my current laptop (a model notorious for overheating) slowly speeds up with excessive CPU load, like a red-lining car engine complete with vibration and heat. This klunky fix of a bad design is actually helpful, warning me to check on runaway processes, and shut them down before something worse happens.

2.2 Transition

Sometimes, the computer does need to explicitly engage a human's attention. But even under controlled, sensed, and modeled laboratory conditions, computers have barely attained the abilities of a human toddler in reading and giving human social cues; they have little awareness of when or how it is acceptable to interrupt [6]. In contrast, a *human* can notice that another person is deeply engrossed, prepare that person for a question by standing nearby, approaching as she sees she's been noticed, or returning later if the question isn't urgent or important.

1. *Haptic* is used here under the engineering convention to encompass both tactile and proprioceptive/kinesthetic modalities.

2.3 Switching

Worst, computers require us to segment and carry out work as they do: concurrently perform multiple tasks by dint of fine-grained context switching. People have always "multitasked." We talk with a companion while walking or throwing a ball for the dog, and we prepare complex meals, concocting the different elements by interleaving a hundred small jobs. But current information and communication technology not only makes multitasking a seductive and ingrained part of everything we do, it reduces the time slice, adds threads, and crams them all into a single perceptual channel. During a brief period, we can carry on multiple instant messaging (IM) conversations, write a document, look up reference material on the Internet, and ponder travel times for an upcoming trip; all by jumping through windows on a graphical display.

Each context switch has a cost. The cost for the computer is fixed and accountable in microseconds, and it can be optimized through software architecture and code design. A human must pick up the IM conversation while waiting for the travel search engine to alert him when it has come back with a result; when he returns to the search engine, it takes a moment to remember what he was doing with it. These small cognitive struggles do not just consume a bit of extra time. They are distracting and lead to further self-interruption. They are disorienting; it may take minutes to mentally fetch and reload a previous context. They are collectively exhausting, and dissipate the energy, focus, and resolution brought to the original task [2], [7]. They often lead to compulsive behavior [8], [9].

3 The Ambient Approach

What makes an interface ambient? Wieser notes that "only when things disappear [into the periphery] are we freed to use them without thinking and so to focus beyond them on new goals" [4]. When they are needed, there must be no surprises; but, instead, a gradual preparation, like the clock radio which starts quietly a few minutes before wake-up time, and increases volume nicely before resorting to a noxious buzz.

When a human multitasks with physical materials and tools, in office, kitchen, machine shop, or garden, the various threads of her labor often leave tangible traces that remind her of their existence and the point she had reached with them before switching: the woodworking project left out on a bench and the (paper) letter lying on the desk awaiting an answer. They even give subtle, often multisensory, indications of their state. The gently intensifying aromas from a baking cake signify it will soon be time to take it from the oven. Shared, changing environs tell *both* walkers that their conversation must soon come to a close.

This availability of background information is a direct result of these processes' gradual, continuous movements between states (the cake bakes and renders its fragrance gradually, but a Web search engine delivers its result abruptly, with no intermediate state display) and the physical proximity of artifacts. There are similar features in many kinds of human-human communication. When other people share our physical space, we are continually aware of their presence in many small ways, such as sounds of children moving through the house, of coworkers talking, walking down the hall, and leaving the building at the end of the day. When the events and stimuli *do* move into our attention, foreshadowing has often developed a subconscious expectation for it. When the same individuals exist in a physically remote space, connected asynchronously through electronic messages, the web of continuity and readiness is fractured.

This can be summarized with a few observations:

- Ambience provides *context and awareness for an ongoing situation*, available for automatic monitoring or processing.
- Ambience *communicates relevant change*, quietly and in a natural, orienting way, by fitting into the landscape of information and building upon its familiar texture. (Imagine a forest meadow full of sounds: when the fox steals in the soundscape changes, with some going silent and others elevating to a high chatter.)
- Ambience is *low effort*: there cannot be much mental work involved in decoding a signal.
- Ambience supports *automatic behavior*.
- Ambience *lets us follow up*. We become gradually aware of a developing situation and can access extra information as needed—possibly because we already have its context.
- Ambience acts on our *unconscious processes*, including the affective or emotional. A background signal might transition from pleasant to mildly disturbing, creating a growing awareness in this way. It works through our affect response to alert us, much as ominous music in a scary movie cues a particular emotional response along with the appropriate orienting cue or readiness for action.

Digital interfaces tend to be binary—there, or not there—as a natural outcome of their internal design and the opacity of a microprocessor's work. Further, they must compete for the center of our attention because that is all they can access, with no mechanism for sliding smoothly in and out of focus.

3.1 Illustrative, if Untouchable, Examples

The idea of ambient interfaces has been around for a while. Many instances have been prototyped, albeit usually as a concept rather than as a working implementation; and touchability is rare. Proposed utilities have included remote collaboration, situational awareness, system status, and connection with friends and loved ones who do not share our physical space.

Some early examples illustrate the essential vision of ambient awareness. These often manifest as continuous access to and consequent awareness of remotely generated activity, people, or communications. In the early 1990s, Jeremijenko linked the "Dangling String" in a hallway to electronic traffic on PARC's first-generation internal network (described in [5]). Located in a communal hallway, its swirling made an invisible activity apparent and implied more than the movement of electrons on wires: real people were sending those messages and running those compute jobs. While this information might not be immediately critical for anyone's tasks, it was a proxy for the physical movement of people through hallways. Those individuals were now typing in their offices in a deceptive quiet, while a maelstrom of thought and action circulated in the cables.

In 1996, Strong and Gaver articulated how collaborative systems of the time failed to support remote *collaboration*, before going on to propose some ambient alternatives:

> Most current collaborative systems demand explicit communication. They rely on symbolic messages—usually language—which means that communicative acts must be overtly articulated by the sender, and that their reception is a relatively focused and attention-demanding endeavor for the recipient. The use of symbols also implies that the process is one of transferring information, whether about facts or opinions or beliefs. Finally, the broad purpose of current systems is to support goal-oriented behavior such as planning, design, or problem-solving, in which communication serves some external aim. ([10, p. 30])

3.1.1 Working and Living Environments

Ishii et al.'s "ambientROOM" is a multimodal exploration in the context of an office or laboratory [11]. Ripples of water or light indicate activity of a loved one, of a pet hamster in a remote cage, or a crowd in the office building's atrium; room lighting and volume levels of recorded birdsong and rain signify quantitative information like email or stock quotes. Customized, graspable controls with appropriate affordances allow the user to manage the displays.

In the home, MacIntyre et al. used the device of montages projected graphically on a peripheral wall display to promote awareness of past and present background activities; the wall display avoided the attention-centered desktop screen [12]. Meanwhile, Hindus et al. experimented with lightweight social communication, for example, to support the desire of individuals to have some awareness of a senior relative's activity in a different home [13]. In one instance, a lava lamp pulsed with the elder's remotely sensed heartbeat. Issues of privacy and interpretation were exposed. What does it mean when the heartbeat stops? An emergency, or a technical malfunction?

Indeed, user interfaces for technologies that will be used in the home have subtly different requirements for acceptability than those in the workplace. Monk et al. arrived at a list—*simple, social, ethical,* and *beautiful*—that aims to capture such necessary attributes in the context of supporting seniors with encroaching dementia or physical disability, struggling to maintain their personal dignity, aesthetic pleasure and independence, as well as safety and comfort [14].

3.1.2 Aesthetics of Ambience

Heiner et al. take a more explicitly aesthetic tack with the "Information Percolator," where air bubbles rise in tubes of water forming a wall display [15]. By properly controlling the release of air, a set of pixels scrolls upward. The intent is to put the ringing of cell phones or the beeping of pagers into the background, while not allowing complete escape, because

> ... if in the (near) future a large number of devices each require, or even demand, a little bit of our attention, the

Fig. 1. Wallace et al.'s "Journeys between Ourselves." Provided with permission by Jayne Wallace; see [18].

> benefits of inexpensive ubiquitous computing may be overwhelmed by its personal cost.

Wright et al. speak eloquently of the process of designing *individual* aesthetic experiences, and the need to incorporate a personal aesthetic into the design of ambient displays. Through case studies of two artist designers, they discuss how studying individual experience leads to evocative representations in an effort which is explicit and cognitive for the artist [16]. They argue that personal engagement with every individual is not necessary to create generally useful designs, but "by working with individuals we can get at experience, much of which is shared and identifiable by other people." When a highly individual experience is presented as a fragment or a moment, with minimal instruction in expected reaction, the recipient tends to place it within his or her own personal context.

"Blossom (glass, paper and wood, to be held and caressed)" was thus created through a process of conversation, sense-making, and suggestion between subject and artist that was inspired by Dewey's work in the 1930s [17], to unintrusively bridge an immigrant woman to her family land in the old country. A blossom made of postage stamps grows out of a twig taken from a tree near the old house, enclosed in a delicate glass bulb. The blossom spreads its petals when it rains at the old house; leading its holder to initiate a more direct connection (perhaps a phone call or letter) at a time of her choosing.

3.1.3 Wearables

Wearable computers—ranging from street-ready but quintessentially geeky head-mounted displays to clothing and jewelry at the height of hip—are a regular target of ambient display development. They go where you go, and have an intriguing potential for personalization. British artist Jayne Wallace and a team of psychologists and engineers recently explored mediums for connectedness between an aging parent and a caring but busy adult son or daughter, and created a pair of linked pendants from personal objects belonging to one pair. A rub on one causes a pulsing on the other (Fig. 1, [18]). The team reports the need for high individuality in the design. For these two participants, this meant an appearance that was organic and emphatically not electronic, whereas an engineer's natural language might have involved simple-to-implement and low-power display mechanisms like a lit LED. More recent explorations by Olivier and Wallace can be found in [19].

Fig. 2. The Emo bracelet displays biometrically sensed mood to a partner [20]. Reprinted with permission from Panasonic.

A team of mechanical design graduate students at Stanford University came up with a more high-tech look for connectedness with their peers: a haptic bracelet (Fig. 2, [20]) intended to work in conjunction with a mood-reading device based on a user's sensed affect using parameters such as heart rate, galvanic skin response, or facial expressions. "Emo" displayed light and vibrations to communicate its wearer's state (visual) and that of one other person (tactile) also wearing an Emo bracelet, distinguishing between bored, relaxed, and excited.

3.1.4 Persuasion

There is a growing recognition of the power inherent in interfaces that persuade rather than coerce changes in people's behavior, beliefs, or attitudes [21]. Because they can act gently in the background, creating awareness and context, and an atmosphere of reminding that doesn't nag, the ambient interfaces are viewed as a likely vehicle for this.

One such movement is to build individual mind-sets for "green" lifestyles, and facilitate personal efforts to live in a sustainable way—e.g., by providing high granularity but unintrusive feedback about current energy use patterns, giving visibility and a pleasing form to parameters that were previously inaccessible. In "UbiGreen," Froehlich et al. used mobile phones to both collect data on transportation usage (a prime energy use culprit for city dwellers) and provide a personal ambient display of how the user is doing [22]. To support this kind of integrated behavior, the researchers began by exploring test users' existing transportation routines and motivations for improving the sustainability of their transport patterns. These results were used as input to the development of a platform that illustrated the user's actual transit behavior as wallpaper on a phone's screen. At the start of each week, a tree is bare; leaves, blossoms, and finally fruit are added after each green transportation event.

In the home, Smith's "Wilting Flower" displays household energy consumption with a physical, mechanical flower which sits in a family common room (Fig. 3); it blooms or wilts in an inverse relationship to the day's energy usage [23].

3.2 Multimodality

Invoking multiple senses while making full use of space and direction is critical to ambience. Interacting through a

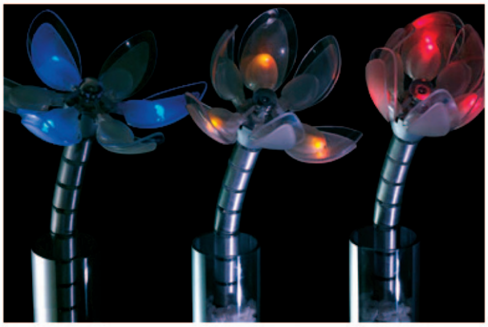

Fig. 3. Carl Smith's "Wilting Flower" displays household energy consumption, aiming to subtly influence the household's behavior. Provided with permission by Carl Smith.

graphical screen requires communication to be primarily visual.

To illustrate: on an icy day last winter, I bicycled to work. I *felt* vibrations from the road surface through hands, seat, and feet, my internal effort of riding up a hill, the wind as I rushed down, and the slickness of any ice via the bike's handling. I *heard* other traffic and *saw* signs of black ice in the sheen on the road. The next day, I drove to work in a well-sprung car that handles excellently on the ice. Insulated within a box, I listened to the news and enjoyed the view. I parked, got out, and went flying because I'd forgotten the ice was there.

This is not to denigrate the car. On bike day, I arrived bruised and abashed after two long sliding skids (a most haptic experience). Nothing like that happened as long as I was in the car. But the degree of separation from my environment was profound, whereas the bike falls were actually delayed and mitigated by my multimodal awareness of the tricky road conditions.

Remotization, automation, and labor saving equate to separation. Information that's not needed is withheld—until it is urgently needed; then, it's generally delivered to our eyes with little warning. Eyes are easiest but they aren't always the best.

3.3 Ambience That's Made It Out There

Technological advances are making more of these ideas possible today; a summary of relevant technologies can be found in [24], including motes, WiFi, and affective interfaces. Ambience occurs as a result of unintrusive data collection, as well as the way information is presented to the user.

So far, the reality doesn't always meet expectations. Digital picture frames were envisioned a decade ago as a way to stay gently in touch with loved ones from afar, while providing an outlet for the glut of photos provided by digital cameras. Long the darling of HCI undergraduate design projects, today they can be had for the price of a high-end toaster. But my own mother-in-law is uninterested in keeping up with her grandchildren in this format, declaring them ugly, complicated, and disconcerting. Meanwhile, a colleague reports an appreciative reception when he set up a projector off a networked hard drive in *his* in-law's house. Ottawa versus Palo Alto (the locales of these anecdotes), or a different implementation? Or, perhaps, some ambience is in the eye of the beholder.

Graphical interfaces have done better. Focus + context displays [25] reached the consumer in the late 1990s as the little square inset on many interactive maps that indicates where the enlarged region is taken from. This idea is now present in zoomable interfaces of every ilk, from Web-generated driving directions to large image files. In research laboratories, the "context" part of the display might fill the room, as a peripheral, orienting backdrop.

The most successful examples of mainstream (or nearly so) ambience are auditory, not visual. One early starting point is scary movie music. Gaver's now-ubiquituous auditory icons [26]— "caricatures of naturally occurring sound," like paper crumpling to indicate a virtual document being thrown away, and a heavy versus light thunk to indicate the size of an email arriving in the mailbox—began with a goal of simple usability. But the strategy of communicating information "in the way that people listen to the world in their everyday lives" has resulted in something that often works the same way, or, in some cases, better than the real thing. Unlike the human postman, you can turn auditory icons for your email off when even an *ambient* awareness is too distracting.

In a more cautionary tale, cell phone ring tones certainly provide a background soundscape in many environments, but it is rarely an unintrusive one. In a physical space with multiple users per space and multiple kinds of alerts per user, none aware of each other, individuals respond in a "prisoner's dilemma" manner [27] by adjusting ring tones to ensure that his own can be heard above and distinguished from all the others.

There are also persuasive technology solutions for health care needs, such as physiological and activity monitoring. "SenseWear" uses an armband sensor to monitor calories burned, dietary intake, and duration of physical activity and sleep. It supplies this input to the physician, but also provides personal feedback as the activity takes place [28].

For the athlete, there is a glorious union of technology, social networking and consumer product giants Nike and Apple: a piezo accelerometer in a high-priced shoe converts foot contact time and duty cycle into running speed [29]. These data are telemetered to the runner's coupled iPod device, which logs estimates of time, distance, pace, and calories burned and gives (visual and auditory) feedback at prespecified goals. Runners can upload their numbers to the Nike Website and compete with partners asynchronously [30].

4 Haptic Examples from the Personal to the Public

By their nature, ambient haptic displays require close physical contact. Often this will mean that they reside in the user's personal space or are worn on the user's body, which constrains much about their form. It is revealing to organize present and past examples on a rough spectrum of intimacy, ranging from the largely utilitarian to those playing more private and emotionally oriented roles; aesthetics and pleasurability of the sensation are important at all times. This dimension is crucial to many aspects of design including visual affordance, level of familiarity expected, and the kind of information that will be displayed.

TABLE 1
Making Sense of Ambient Haptic Display Examples: Social Configuration versus the Anticipated Intimacy of the Interaction

	Individual	*Shared*	*Public*
Utilitarian	- GUI support [31]–[36] - mobile communication [37]–[46] - driving support [47]–[54] - wearables [55]–[59]	- shared architectural elements [64] - *flight simulators, in instructor mode* - remote collaboration [65]	- shared spaces [64], [70]–[72]
Intimate/ Emotional	- touchable robots [60]–[63]	- affective awareness [18], [66]–[69] - *touchable robot as shared object*	- social networking [73]

Table 1 shows a loose grouping of examples mentioned in this paper (by no means an exhaustive list) by social configuration of the anticipated use scenario as *individual*, *shared,* or *public*, where a spectrum of intimacy in the technology's role is evident within each category. Many of the systems in Table 1 could move along either axis with changes in use scenario, e.g., the items in italics.

Many of these examples are not designed with the explicit intention of working in an attentional back channel, nor tested for their ability to do so; others work in foreground or background at different times, e.g., responding directly to a request or quietly emanating a state. Most *do* address the problem of replacing or restoring a form of communication that previously occurred in the background, and in everyday use, interactions such as these could easily become ambient if designed to be.

4.1 Individual

In this catalog, a haptic display is deemed "individual" by relating to one person at a time in a specialized way. These include customized vibetones on a cell phone, which while signaling communications from other people, operate in the user's personal environment according to his preferences; and customized interfaces which might be used at different times by different individuals. This end of the social configuration spectrum tends to have fewer opportunities for a more intimate nature (note the relative sparseness of the lower left region in Table 1), perhaps because communication with others is not involved.

4.1.1 The Desktop Workstation

Multiple experiments with general GUI-based haptic support in computer mice took place in the late 1990s. These included both hardware (a vibratory [31] and a force feedback [32] mouse) and interaction techniques (e.g., [33]). A fundamental difficulty with both approaches lay in superposing a new medium of feedback on top of the interfaces designed to be purely graphical and visually guided. The augmentation could at best provide an incremental performance benefit, and meanwhile the hardware introduced other performance hits, like a reduced mouse workspace [32].

More recently, there have been efforts to develop graphical-haptic desktop-oriented interfaces that employed both modalities in appropriate ways, e.g., Smyth and Kirkpatrick's Pokespace [34]. Conversely, these approaches have adoption concerns: the haptic feedback is essential, so widespread use can't occur until the feature becomes more prevalent.

In the spirit of more specialized interfaces but departing from traditional desktop functions and metaphors, Snibbe et al. prototyped a set of metaphors for manipulating media streams using simple force feedback displays [35]. These metaphors were inspired by tangible real-world interactions like splicing celluloid film drawn off heavy reels; or emerging practices in other design fields, like graphical fisheye visualizations.

A different slant on quietly augmenting the conventional workspace was attempted more recently with a finger-mounted tactile display used to indicate mistyped letters directly to the offending finger (corresponding to half-typed words whose initial parts don't appear in a dictionary) and making these harder to type. Hoffman et al. claim a sharp reduction in backspaces and zero mistyped words, by dint of heading off mistakes rather than easing their correction [36]. While this display is cumbersome, the approach is promising: it aims to close a low-level sensorimotor feedback loop, which would not require cognition.

4.1.2 Mobile Communication

Mobile handheld devices have been using simple tactile displays (obeying constraints of power and size) for some time, with more sophisticated protocols emerging recently for the information display of various types of information display (haptic icons [37], [38]) as summarized in [39].

The most common tactile instantiation to date is the nondirectional vibration, rendered through many competing technologies beginning with the eccentric rotating pager motor, and proceeding to varieties of active touch screens, where tactile feedback may be linked to the graphical channel. Poupyrev et al. developed some early guidelines for ambient touch screen feedback in mobile devices [42], and other efforts have investigated support for detailed notifications, handheld GUI feedback [41], binary feedback of successful button-press completion [44], and quantitative parameters such as time of day [45].

Increasingly sophisticated technology is required to indicate directional concepts, such as geographical navigation and enhanced Web browsing [40], [43]. Stretching the envelope a bit more, Williamson et al.'s "Shoogle" reveals the presence and properties of messages or resources in a handheld device when shaken, through vibrotactile display and impact sonification [46].

The general class of multitouch devices, i.e., using kinesthetic input to drive an interaction, may not have an explicit, active haptic component; however, they give response to kinesthetic input much like haptics. This impression can be augmented with auditory coupling [74] to the point that an auditory, kinesthetically coupled cue cannot be distinguished from a true tactile click. This is a fact well known by users of devices like the iPod, a portable music player with a touch-sensitive, buttonless control surface. Like real tactile button clicks, such an interaction satisfies many properties of ambience in that information (confirmation of the control activation) is conveyed in the attentional background, and the absence of anticipated confirmation tends to move the action into the user's foreground. Innovative design of the touch interaction allows very small surfaces [75].

Most if not all of these interactions are designed with the intent of low cognitive effort to suit their context of on-the-go use, allowing them a potential designation of ambience.

4.1.3 Car and Driver

Haptic feedback can be layered on manual controls or other contact surfaces in a shared space like the family car, providing safety information drawn from external or remote sensors, or interaction aids for secondary controls. Body sites include the hands and feet via steering wheel and throttle [47], [48], [49], [50] or secondary controls [52] including the BMW/Immersion iDrive [51], and spatial orienting information delivered to the torso through the seat or a vest [53], [54].

4.1.4 Wearables

Another class of explicitly individual ambient display encompasses wearable items that provide body-centric information like vests and belts with tactor arrays that collectively indicate direction [55]. Tan and Pentland discussed application of a sensory saltation phenomenon to a vest [56] and van Erp et al. described waypoint navigation with a waist belt [57]. Jansen et al. showed positive results for a vest display for directional display for helicopter pilots in zero-visibility landing conditions, tested in real flight conditions [58]. In contrast, "Cutaneous Grooves" is a pioneering example of wearable haptics intended for aesthetic rather than utilitarian purposes in which spatiotemporal patterns of vibration across the body surface are musically structured [59].

4.1.5 Touchable Robots

An emerging sector in human-robot interaction (HRI) deals with touchable toy-like robots, which might exhibit emotional intelligence and expressiveness, and frequently have therapeutic goals. Shibata et al.'s "Paro" is an animated soft white seal designed for robot-assisted therapy for elders and children [60]. Stiehl et al.'s "Huggable" focuses on gesture recognition in touch interactions on a sensed teddy bear body, with companionship applications in mind [61]. Yohanan and MacLean have developed a sensed and actuated "Creature" platform that deliberately avoids representation of a specific animal, albeit inspired by the soothing background presence of a lap pet [63]. Its immediate goal is to coordinate an affectively satisfying coupled interaction, where gestures are recognized and the Creature responds with appropriate emanations like purring, breathing, and softening its ears [62], [63].

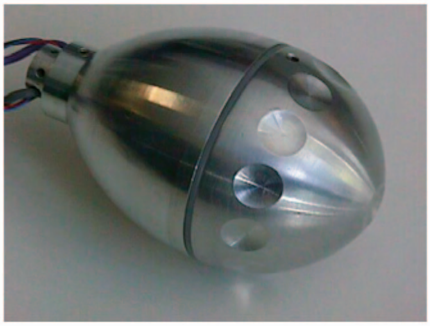

Fig. 4. Aladdin: a doorknob that communicates information to users about a common physical space through visual gesture and sound at a distance, and forces, vibrations and heat when in contact [64].

4.2 Shared

Some ambient displays are envisioned to exist in spaces shared by a small group of people who are close, e.g., a romantically involved couple, a family, or workers in a physical or virtual office. The goals of the background information communicated through such a mechanism might include a sense of closeness between a separated couple, awareness of family members' activity levels in the manner of Hindus et al.'s lava lamp [13], or facilitation of a distributed meeting by restoring nonverbal indications that would be available when copresent. Most commonly, multiple physical instances of a device connect the users in a lightweight network, whether the communication is synchronous or asynchronous; in other cases, a single device might be encountered and used at different times by individuals.

4.2.1 Remote Collaboration

A functional example lies in the realm of remote collaboration support: haptic background messaging aims to restore to distributed teams the nonverbal cues that collocated teams normally use to negotiate turn-taking [65]. Team members use "icons" delivered through a vibrotactile mouse to indicate the urgency with which they wish to take a turn, without interfering with the visual or aural business of their shared task and verbal discussion surrounding it, with positive impact on collaboration quality. Because its primary premise and value are back-channel operation, this instantiation was explicitly designed and tested in the presence of attentional load.

4.2.2 Architectural Elements

The boundary between shared and public display is tricky for objects embedded in the architecture. The distinction here is of open-access spaces (public) versus those restricted to users with some familiarity with one another (shared).

The haptic doorknob as ambient boundary to a common physical space, which could also be shared by remote coworkers, was explored by MacLean and Roderick [64]. The knob itself was a force-feedback handle with a thermal display, mounted on a door (Fig. 4). Accompanying sounds were designed to augment meanings, lure, or warn away; and the knob could move on its own in a visual animation. Entering a lab or conference room, one might get a sense of the room's recent history (Are there people in there now? What has the activity level been over the past few hours?), or similar kinds of impressions for a linked remote space. Alternatively, as the gateway to a personal space like an office, the knob could indicate desired privacy levels and record a "message" for visitors who found the office empty.

4.2.3 Fostering Closeness with Affective Awareness

At the more intimate end, there is emotional dyadic communication. It is easy to imagine hapticized extensions to examples given earlier for jewelry and clothing; Wallace et al.'s linked pendants were introduced earlier more generally [18]. Fogg et al.'s HandJive and Brave and Dahley's InTouch devices both linked couples with mediating forces, using simple mockups allowing them to explore aspects of the experience [66], [67]. Chang et al.'s ComTouch adds a tactile channel to spoken communications, with a handheld device that allows the squeeze under each finger to be represented as vibration to a partner—who can also receive or send [68]. Smith and MacLean systematically studied the role of factors like intimacy of interaction metaphor and a pair's relationship (strangers, romantic couple) on ability to communicate specific emotions through a simple force-feedback link [69].

4.3 Public

Truly public haptic interfaces are open-access, touchable by many people and by anyone. A given individual might encounter it once, or daily. Here, cultural norms for touching public objects come into full play, including inhibitions like squeamishness of germs, perceived ownership and fear of unexpected, perhaps painful behavior [77]. Yet people are willing to communally touch many things, like doorknobs, handrails, debit card keypad, playground equipment, and information kiosk screens and buttons. They lounge, albeit with a garment in between, on cushioned seats in airport terminals and doctors' offices. At the extreme end of shared-touch tolerance, people use public toilets; in clothing stores, they try on intimate apparel that others may have worn.

Design in this space needs to keep durability and thoughts of germs in mind. Public haptic displays will *generally* be encased in plastic or metal and not in fur.

4.3.1 Shared Spaces

Unsurprisingly, haptic experimentation in public spaces has been muted so far and tends to appear in artistic installations (Stedman's "Blanket" literally crawls over and cuddles children and adults, who willingly climb underneath it in public displays [78]).

That is not to say that the realm is untouchable. The haptic knob is one approach that could be extended in a public venue: doorknobs are one of those things we *are* willing to touch. Imagine a robust variant in a door in a commuter transit station, like the entrance to the subway or railway, passed through every day.

Or, through vibrations in the floor that signal wait time before a train, or ticket queue length. A foot focus neatly avoids the manual touching taboo. Inspired by existing practices of providing passive bump maps imprinted on sidewalks and intersections to inform blind pedestrians of traffic patterns, Visell et al. prototyped an active display that walkers stand on, aiming to simulate typical ground

Fig. 5. Stress outsourced: "friends" on a social network give a massage in response to a call of distress. Responses actuate different zones on the recipient's back, based on their origins [73]. Reprinted with permission from the ACM Press.

materials like gravel, carpet, or stone [72]. This version is shared in the sense of accessibility, but not in passersby contributing to what's displayed; however, it could also reflect more interactive information, like pedestrian traffic nearby, on the other side of town or in a sister city. In a navigation example mentioned before, a personal haptic display acts in concert with a shared visual display to access environmental information [43]. Meanwhile, the "Musical Roadway," in which as a marketing stunt Honda cut grooves into roadway segments such that tires passing over them would render a familiar tune like the William Tell Overture, is an auditory example that could easily translate to the haptic domain for a pedestrian or cyclist [71].

Taking a more theoretically pass, Vogel and Balakrishnan employed simple hand gestures and touch screen input for explicit interaction, while relying on body orientation and position cues for implicit interaction in a public space. They sought mechanisms for establishing a smooth transition between these foreground/background modes, for example, by modeling state transitions between several concentric "interaction zones" of progressively increasing focus. They also identified a boundary between public and personal information that is shared [70].

4.3.2 Social Networking

"Stress Outsourced" is another tricky boundary case: a one-to-many-to-one concept wherein users subscribing to a Web-based service can request (through a possibly unconscious but personally typical stress-induced gesture) and receive (through a line of tactors worn across the shoulders) a comforting massage from strangers (Fig. 5, [73]). Other members of the group receive the distress signal through a different body-mounted tactor and can choose to give manual succor. The resulting massage is distributed on the recipient's tactor grid on an axis of geographical distance of the respondent. Intended to blend into the user's physical context and operate in the background, this interface leverages a social network and challenges the existing etiquette of proxemics. Being touched or poked implies the presence in one's personal space; here, this access is granted to strangers.

5 Ambient Haptics: Design Principles and Challenges

As ambience has emerged as a design philosophy, so have complications, connections to other knowledge bases, and principles—of which Monk's list (simple, social, ethical, beautiful [14]) is one starting point. Here, we touch on a few, which have particular relevance for *haptic* ambient design as follows:

- orchestrating the touch,
- communicating without effort,
- specifying and verifying ambient communication,
- moving between periphery and center, and
- balancing utility and privacy.

5.1 Orchestrating the Touch

To deliver information ambiently, a touch must be natural, inevitable, and timely.

Natural haptic information processing is already often ambient [79]. Consider *direct manipulation*, where we perceive weight, vibration, and progress through chopping vegetables with a knife, sharpening a pencil, or playing a musical instrument. In *affective communication*, the awareness of the affection displayed by holding a hand, the comfort of a hug, and the sense of personal invasion triggered by an aggressive touch is often peripheral, with notable exceptions when the personal touch is unexpected, dangerous, or itself a primary focus. There need be nothing explicitly contemplative in your emotional reaction to the cat sitting in your lap, generated through its warmth, the amplitude of its purr, and the regularity of its kneading paws. With similar indirection, the feel of the clothing you wear can affect your inner sense of formality and appropriate behavior—sneakers versus clicky high-heeled boots; soft old sweater, or crisp shirt, and firmly knotted tie.

The typically proximal nature of haptic input (received through body contact) is both a feature and a challenge in design. It can be dispersed across the body surface, and may be continuous and ongoing in nature—all opportunities for ambient display. On the other hand, the percept is often endogenous, especially for tactile displays, which does not always lend itself to directing awareness away from the body. This proximality may contribute to a sense that the communication arises within one's personal space, with varying appropriateness. In fact, there are many distal *sources* of haptic input; as observed in 1925 by Katz, "vibration has many of the capabilities of a far sense" in that vibration of one's surroundings (themselves in proximal contact) can indicate a remote event [80]. Yao and Hayward demonstrated this far-sense capability using computer-controlled vibrations to create virtual environmental cues (here, implying the length of a handheld tube) [81].

Reliable, continuous contact is not always feasible. A cell phone would seem like a good site for ambient information because you hold it in your hand; but only sometimes, and in different ways. An information display must be attuned to the patterns of use, which, in turn, have to be well understood.

Thus, a large part of haptic interaction design is *orchestration of the touch in time and space*. The interface site should be desirable to touch, or unavoidably in contact at the moment when communication will occur. The cell phone coordination problem might be solved with a Bluetooth-enabled ring that pulses soothingly when your partner telephones you on a handset in your pocket, and constricts or becomes icy cold when an urgent call is from your child's school. Your debit card could communicate how much money is in your account, by feeling heavy as you slide it through the reader. Of course, you would need to authenticate it first, without having to think about it. This may be possible haptically as well [82].

5.2 Communicating without Effort

An ambient interface must be effortless for the user to decode. While very low cognitive demand is always desirable, here it is a necessity. Without it, the communication will require explicit attention to be understood, forcing it into the user's foreground awareness, or else the information will be dropped. Moreover, mental effort in processing an information stream depends on the circumstance—factors like familiarity with the situation or signal, and momentary mental state, whether alert, overwhelmed, weary, or otherwise impaired.

5.2.1 Interruption and Volume Control

The increasing incidence of rapid human context switching induced by contemporary communications technology has led to study of its impact on user productivity and distraction. Cuttrell et al. found that the degree of disruption entailed in interrupting a person's work flow can depend on where in the original tasks' execution the interruption occurs, lending insight into how a smarter system might better time such interruptions [2]. Adamczyk and Bailey found further effects on performance and emotional state [83].

Users sometimes find their own ways of controlling the "volume" of interruption, meaning not sound level but frequency of contact or restrictions on access [84]. At least, they may attempt to do so. Users report a sense of being awash in a flow of information to which response is optional and immersion is variable. However, real voluntary control can be hard to achieve, and it is common for individuals to choose a level of immersion and responsiveness to the flow that is at odds with what is rationally needed, helpful, or expected in a given situation [9].

Conversely, if the *system* lowers the volume without shutting it off, individuals might feel less need (real or compulsive) to seek status updates. Ideally, the display will generate awareness of the flow without the context switch of checking, and engender trust that an important update will be more saliently signaled.

5.2.2 Learning and Familiarity

Even a complex signal in any modality can be highly learned, and at that point, small deviations from a set point that are barely noticeable by a novice might be salient to an expert, often through a nonattentional process—something "just doesn't seem right." This can be seen in honed professional behavior, such as an anesthesiologist processing a soundscape of auditory equipment monitors and alarms, or a musician noticing a wrong note in another's playing of a piece she knows well (and as documented in studies comparing novice and expert abilities in discerning haptic systems [85], [86]). It is also evident in learned patterns encountered more widely: the car's engine feels or sounds off, or we notice on entering a familiar space that objects have been subtly disturbed.

Symbolic haptic information display—just one possibility for ambient haptics—provides a useful set point. We have observed unexpected human ability to rapidly learn abstract haptic codes and recall them under imposed distraction, implying low mental retrieval effort [39]. The learning required to reach and retain this state is not large when the stimuli are well designed, but it is not zero. What, then, is an appropriate required learning time in a given circumstance?

5.2.3 Low-Effort Uptake

Based on knowledge of visual processing, principles have evolved for effective *visual* information display. In addition to graphical interface usability guides, the fields of information visualization [87], [88] and visual analytics [89] have delivered a wealth of design insights and display/interaction techniques for conveying information at low effort in different kinds of situations. Contexts range from high resolution and physically very large screens to constrained displays like a handheld smartphone, in attentionally focused or multitasking environments.

The same cannot be said for haptic interfaces. Much of haptics research to date has focused on simulating and accurately rendering the physics of haptic interaction and establishing human psychophysical abilities. This has frequently been done independently of the sort of cognitive load, attention, and secondary task manipulations seen in other kinds of interface developments; some exceptions are noted at the end of the next section. Designing such heuristics will be a key ongoing challenge for the field.

One approach toward establishing cognitive effort can be built upon mental resource and signal detection theory, implemented by testing users' ability to absorb or act on information under high levels of workload from other sources [90], [91]. The premise is that when information processing is sensitive to workload, it will consume an excessive amount of some limited resource; which will, in turn, register as reduced performance in one of the tasks. Competition is most severe when tasks contend for the same resource, e.g., sensory channel, memory, or cognitive center.

Related findings include Tan et al.'s measurement of information transfer (IT) rates for certain haptic signals [92]. IT rate is not a measure of mental effort, but rather a quantitative indication of how much data can theoretically be embedded in a given signal on the basis of the display capability and relevant perceptual acuity—one measure of the medium's information richness. The *accessibility* of that information depends on other factors, such as the cognitive processing effort required to extract the information in even a single-task context, and the mental resource competition that comes into play when concurrent tasks are underway [90]. Awareness of each of these factors, in isolation and together, is needed to design information displays that are low enough in overall cognitive demand to run in the background.

5.3 Specifying and Verifying Ambient Communication

How can you tell if you've succeeded in producing ambient communication? For a start, two things must be true: 1) the interface *is* communicative, at least some of the time, and 2) it *is not* in the center of the user's attention, most of the time.

The first one is measurable by a variety of means, even when the communicated information was nonattentional. Techniques in vision involve asking subjects if they are able to identify the value of a parameter supplied in a nonattended channel [93], often receiving a "no-confidence" response; then requiring them to guess. When the guessed response is correct more often than chance, information has probably been received. There are many variants on this technique, with an important feature being the degree to which the subject is anticipating some kind of event and is distracted by other events.

Determining whether active attention is involved (point 2) will generally require a less direct approach. In the test above, if low confidence is reported for guessed responses, it may be reasonable to infer that the communication was nonattentive—the subject was unaware of it taking place, or even of seeing the displayed value. This may be an overly conservative measure: high confidence does not mean that attention *was* involved. Another approach, often more complex but also more objective, is to pursue the hypothesis that an attended process will impose substantial load on other mental resources, particularly those which definitely do occupy attention [90]. Such an evaluation involves constructing a controllable abstraction of the anticipated multithreaded use context, then imposing workload assessments on the different threads.

These experiments are hard to design—they require measurable outcomes, continuous performance metrics so that brief spikes of resource overload can be detected, and eventually, an accurate representation of real use contexts. The haptics studies on record that involve multitasking are primarily for taction and in particular for complex signal display and spatial orienting; for example, [39], [41], [54], [94], [95], [96], [97], [98].

Thus, demonstrating efficacy beyond subjective reports remains an open problem. Of course, one approach is to let the market choose—if people find it helpful, maybe it works.

5.4 Moving between Periphery and Center

A critical element of an ambient display is its ability to make a signal salient when its information needs to register. When that is, could depend on the user's availability or on the urgency of the information itself. Either way, the system may need to be smart enough to recognize the need for upgrading salience. We refer again to some systematic efforts to model these transitions, e.g., [70]. It might also sometimes be possible to embed these dynamics into the signal itself, with context-invariant heuristics like "Messages from my child are always important and should be loud" and "When I'm not immersed in a task, I'll notice even a low-salience signal for something that's not so critical." This is subject to the caveats of self-sabotage noted earlier—there's a difference being immersed in a task, and *needing* to be.

Perhaps the simplest notion for supporting periphery-center movements is the graded alert: volume control, managed by the system rather than the user. Lee et al.

found that not only did grading alerts to the driver of impending automobile collisions through a vibrating haptic seat improve safety margins and appropriateness of response, they also increased the users' trust in the information source even in the presence of false alarms [99]. A similar premise was used to mediate turn-taking in distributed meetings, using graded vibrations in the mouse to indicate whether a collaborator wanted cursor control with low or high urgency [65]; here, there was a positive impact on collaboration dynamics, with more equitable control and timely turnover.

5.5 Balancing Utility and Privacy

As with so many of today's potentially very useful technologies, utility often conflicts with privacy and can ethically be problematic, or simply unwelcome. Ambient displays generally provide information about remote or hidden things, like other people. Because both sensing and display take place in the background, the observed party in particular may be unaware of the observation even when it is consensual and well motivated. Elder care and monitoring is a poignant example: whether the monitoring signal is displayed on a daughter's necklace or at a monitoring center at the local health center, privacy has been breached and independence and autonomy may be diminished.

There is also the potential for data error, with implications that range from the needless worry surrounding a dead signal (Mother isn't lying in her bathroom with a broken hip; the sensor batteries just ran down) to health insurance premiums tied to daily activity patterns. The issue of false alarms and its relation to user confidence is enormous. Sensor redundancy in ambient systems could be a key design approach to enhance the user acceptance.

For visual ambient media, reducing the display's explicitness has been offered both as a privacy shield and a means of lowering intrusiveness—graphical avatars of colleagues sitting in remote offices inhabiting a corner of your own screen could be live, high-resolution Webcam shots, cartoons animated by remote office activity levels, or abstractions representing presence, activity, or willingness to engage. In the workplace, indicating your availability to others sometimes encourages further interruption and new social conventions are probably the only solution. Similar developments are playing out in usage of instant messaging, with the evolution of new age-specific norms.

In the interest of privacy, haptic *sensing* may provide a lower-resolution or more-private conduit, which is more difficult to abuse. In the visual domain, one approach has been to use a local processor for real-time video analysis, then communicate only a highly reduced or condensed data set; the original video is not stored. In the elder care scenario, an alarm is transmitted only if certain thresholds (like time-in-bathroom) are passed. Similarly, tactile sensors in a bed and throughout a senior's home (filtered or even raw) might be considered less intrusive than a video feed and therefore more acceptable, while still providing safety-related information about daily movements [100].

6 Conclusion

This paper's purpose was to introduce the concept of ambient interfaces and explore the contributions that ambient haptic information display can and should make to this emerging effort.

It has summarized a number of likely contexts for these contributions, in individual, shared, and public arenas; and suggested some key design principles and challenges. While these apply to ambient interactions in all modalities, some have special relevance or interpretations for those that can only take place when in physical contact with the user. These include the need to manage the act of touching itself; to make communication low effort and to actually *test* for ambient behavior, to design the transitions between background and foreground of attention, and to be aware of the risk of privacy violation in this kind of display.

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Karon E. MacLean received the BSc degree in biological sciences and mechanical engineering from Stanford University in 1986 and the MSc and PhD degrees in mechanical engineering from Massachusetts Institute of Technology in 1988 and 1996, respectively. During 1996-2000, she was with Interval Research Corp. She is an associate professor of computer science at the University of British Columbia, the director of Sensory Perception and Interaction Research Group (2000-present), an associate editor of the *IEEE Transactions on Haptics*, and a cochair of the IEEE Haptics Symposium (2010-2012). Her other awards and achievements include: Peter Wall Early Career Scholar (2001), Izzak Walton Killam Memorial Faculty Research Fellowship (2007), and Charles A. McDowell Award (2008). She is a senior member of the IEEE.