The Design of Personal Ambient Displays

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Bachelor of Science in Brain & Cognitive Sciences,
Massachusetts Institute of Technology, 1997

Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfillment of the requirements for the degree of
Master of Science in Media Arts and Sciences at the
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abstract

The goal of this thesis is to investigate the design of *personal ambient displays*. These are small, physical devices worn to display information to a person in a subtle, persistent, and private manner. They can be small enough to be carried in a pocket, worn as a watch, or even adorned like jewelry. In my implementations, information is displayed solely through tactile modalities such as thermal change (heating and cooling), movement (shifting and vibration), and change of shape (expanding, contracting, and deformation). Using a tactile display allows information to be kept private and reduces the chance of overloading primary visual and auditory activities. The display can remain *ambient*, transmitting information in the background of a person's perception through simple, physical means.

The specific focus of this thesis is to create a number of these tactile displays, to identify and implement applications they can serve, and to evaluate aspects of their effectiveness. I have created a group of small, wireless objects that can warm up and cool down or gently move or shift. Users can reconfigure each display so that information sources like stock data or the activity of people on the internet are mapped to these different tactile modalities. Furthermore, in this thesis I consider the implications that human perception have on the design of these displays and examine potential application areas for further implementations.

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contents

1 introduction

Today's telecommunications world is populated by technologies such as videoconferencing, telephones, pagers, and desktop and laptop computers. A tremendous amount of work is being done to bring communication technology to places where people need it, whether it be at the office, on the street, or at home. These technologies almost exclusively have interfaces that require a significant amount of attention. For instance, a computer is only useful when you are staring at the screen, and a telephone is only functional when engaged in verbal communication with another person.

I believe there is an undiscovered side of telecommunication that does not require as much focused attention. I have started researching devices that speak to this issue, calling them Ambient Displays.

1.1 motivation

Nature is filled with subtle, beautiful and expressive ambient displays that engage each of our senses. The sounds of rain and the feeling of warm wind on our cheeks help us understand and enjoy the weather even as we participate in other activities. Similarly, we are aware of the activity of neighbors through passing sounds and shadows at the periphery of our attention. Cues like an open door or lights in an office help us subconsciously understand the activities of other people and communicate our own activity and availability.

Current personal computing interfaces, however, largely ignore these rich ambient spaces, and limit themselves to focusing vast amounts of digital information on small rectangular windows. Information is presented on flat screens that must be in the foreground of a user's focus to be processed. The interactions between people and digital information are now almost entirely confined to the conventional Graphical User Interface (GUI) comprised of a keyboard, monitor, and mouse.

Using a broader view of display than the conventional GUI, I am attempting to make use of the entire physical environment as an interface. Information is moved off the screen and into the physical environment, manifesting itself as changes in light, sound, color, smell, temperature, or movement.

This is the central idea behind *Ambient Displays*. They are physical devices that can transmit information that is often in the background, or periphery, of a person's attention. Whereas the computer screen requires constant, focused attention in order to be functional, ambient displays do not. A person can check the state of a display by simply glancing around the room, or possibly keep a consistent awareness of a display in the background of his or her attention. These displays provide many different "channels" of information around a room.

Continuous information can be persistently displayed, breaking the current "search and request" paradigm of information retrieval.

1.2 thesis overview

In this thesis, I will detail my experiences with designing ambient displays, relay the design lessons I have learned from them, present some initial user testing, and identify emerging application areas.

This thesis primarily focuses on a new direction in Ambient Displays. Whereas previous work has focused on using sight and sound, this work centers on the sense of touch. All current telecommunication technologies primarily convey information to a user through visual or auditory means, leaving the other three senses largely ignored. I believe that the tactile sense can be used as a means of information display, and further, can be used in a manner consistent with an ambient display.

To test this concept, I have created a set of objects called *personal ambient displays*. These are objects that can subtly and persistently display information to a person in a private manner. The personal ambient displays I have made use tactile sensations as their sole display mechanism. For instance, I have created a small, wireless device that changes its temperature in response to an information source (like a stock tracker or web-hit monitor). Of primary interest in this thesis is the use of heat as a display mechanism. Through the creation, testing, and use of these personal ambient displays, I have identified new application areas and have advanced the conceptual framework of the ambient display of information.

This thesis first presents a description of related work and background research that has led to this new research. Next, aspects of this work are further introduced and examined from the design perspective and the perceptual/cognitive level. Chapter 4 gives a detailed introduction to ambient display prototypes that use sight and sound as their primary display mechanisms, and Chapter 5 details personal ambient display implementations. Following the introduction of the specific displays that have been created is a discussion of the successes and failures I encountered along with the results of pilot user studies.

2 background and related work

"Smelling is believing!"
-tagline from John Waters film *Polyester*, presented in "Odorama"

The idea of using a person's multiple senses as a means of transmitting simultaneous streams of information is nothing new. The soundtracks of movies have long been a kind of ambient source of the mood and emotional content of a film. Movie creators once even tried to include aromatic information in movie theaters (see AromaRama (1958) and Smell-o-Vision (1959)). While these efforts were largely unsuccessful, they did point to ambitious multi-modal directions that display media could have.

This work in personal ambient display has been heavily influenced by past work, and has logically grown out of work done in the MIT Media Lab's Tangible Media Group.

2.1 precursors of ambience

My original inspirations for ambient displays came from the Livewire work of Natalie Jeremijenko [35] and the Kinetic Sculpture work of Arthur Ganson. Their mix of art with technology provided the inspiration that information displays could be both physical and beautiful. The AROMA work of Pedersen and Sokoler (1997), and the Audio Aura work of Mynatt, Back, et al (1998) also address some similar issues. Other researchers have started working on focused applications of ambience as well. The Baby Sense project (Weinberg, et al 1998) shows one particularly interesting use of ambient information: the awareness of a toddler. The Bed (Dodge, 1997) provides ambient awareness of a distant loved one through a bedroom setting, with a focus on the actual bed and pillow.

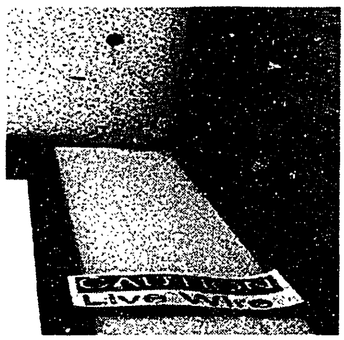


Figure 2.1
Jeremijenko's Livewire creates the sound of network traffic

Perhaps the most directly relevant project to personal ambient displays was a design proposal created by Fiona Raby and Anthony Dunne (Dunne, 1994). They proposed the linkage of two benches. *"When somebody sits on one of them, a corresponding position on the other bench warms up opening up a sound channel.... At the other location, by feeling the bench for 'body heat', a person can decide to make contact by sitting on the warm part, or open their own channel by sitting nearby. Initially the sound channel is distorted, but as the bench slowly warms up, the channel clears, providing a moment to discretely slide away if you change your mind."* This design proposal inspired me to think about heat and temperature as a means of information delivery.

The vision of *ambience* I am pursuing was first formally introduced in the Tangible Bits paper of Ishii and Ullmer (1997). They say:

"We see the locus of computation is now shifting from the desktop in two major directions: i) onto our skins/bodies, and ii) into the physical environments we inhabit."
-Ishii & Ullmer from the seminal work,
"Tangible Bits" (Ishii & Ullmer, 1997)

The Tangible Bits paper goes on to indicate that bits can become accessible in "tangible" ways through *coupling of bits and atoms, interactive surfaces,* and *ambient media.* A series of Tangible User Interfaces have been created to explore this design space.

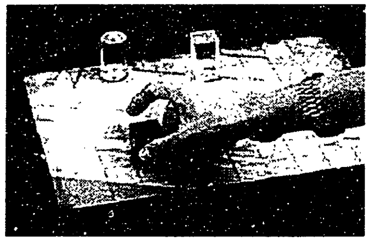


Figure 2.2
One side of the PSyBench chess board

2.2 coupling of bits and atoms

Two Tangible Interfaces, the inTouch and the PsyBench (Brave, Ishii, Dahley, 1998) provided particular inspiration for ambient display design in that they deal with issues of communication, collaboration, and awareness of remote colleagues. They are examples of Synchronized Distributed Physical Objects. A Synchronized Distributed Physical Object creates the illusion of a shared physical object across a distance by physically synchronizing the states of distant, identical copies of an object, using telemanipulation technology. The goal is to enhance real-time remote collaboration and communication by bringing a greater sense of touch and physicality to distributed multi-user interactions.

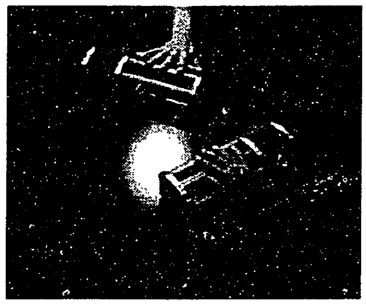


Figure 2.3
The inTouch, an example Of a Synchronized Distributed Physical Object

PSyBench (Physically Synchronized Bench) provides a generic shared physical workspace across distance. The goal is to allow distributed users to cooperate in applications that are heavily based around physical objects. To do this, each physical interface object is turned into a Synchronized Distributed Physical Object so that it can be shared by distant users.

Even more directly related to personal ambient displays is the inTouch, a system for haptic interpersonal communication across a distance. The inTouch consists of two hand-sized objects, each with three cylindrical rollers embedded within a base. Employing the Synchronized Distributed Physical Objects concept, the rollers on each base are hapticly coupled such that each one feels like it is physically linked to its counterpart on the other base. Two people separated by distance can either passively feel the other person's manipulation of a set of three rollers, cooperatively move the "shared" rollers, or fight over the state of the rollers, providing a means for expression through touch.

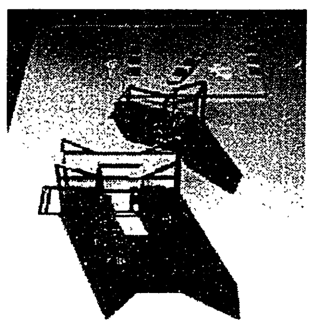


Figure 2.4
The interactive surface of the Luminous Room

2.3 interactive surfaces

Interactive Surfaces are roughly defined as the transformation of each surface within an architectural space (e.g. walls, desktops, ceilings, doors, windows) into an active interface between the physical and virtual worlds. Three works that involve interactive surfaces are the

Luminous Room, PingPongPlus, and Music Bottles. They demonstrate the concept of a surface that can sense and track the objects on it and project digital shadows and sounds.

In the Luminous Room project (Underkoffler and Ishii, 1998), the goal is the pervasive transformation of architectural space, so that every surface is rendered capable of displaying and collecting visual information. Information is projected onto a surface through a projector, and received from a surface by a co-located camera, all built into a single, small light fixture.

PingPongPlus' interactive surface is its "reactive table" that incorporates sensing, sound, and projection technologies. Projectors display patterns of light and shadow on the table; bouncing balls leave images of rippling water; and the rhythm of play drives accompanying music and visuals (Wisneski, Orbanes, Ishii, 1998).

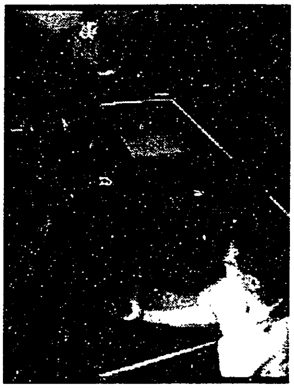


Figure 2.5
PingPongPlus combines a novel sensing technique with unique application content

The Music Bottles project (Ishii, et al, 1999) presents a tangible interface for interaction with a musical composition. The installation consists of a specially designed table upon which three corked bottles are placed. Custom-designed electromagnetic tags embedded in the bottles enable each one to be wirelessly identified and sensed. Uncorking a bottle "releases" the music it contains.

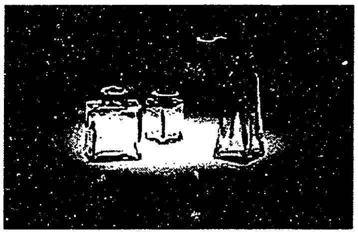


Figure 2.6
MusicBottles create an interactive surface with RFID tagging technology

Each of these projects use a different kind of technology to create an interactive surface. The Luminous Room uses computer vision, PingPongPlus uses sound-based tracking, and Music Bottles uses a multi-parameter RF tag system. Many other technologies exist to create interactive surfaces, such as traditional touch-screen systems and newer laser range finding systems (Strickon and Paradiso, 1998).

2.4 paging & telecommunications

There are many networked, personal devices currently in use including pagers, palm computers, and cellular phones. These devices are often kept in pockets, on belts, or in bags. Phones and pagers, by ringing or buzzing, often demand a user for attention when receiving a signal. Ringing and buzzing work to immediately grab a person's attention. However, if a persistent awareness of an information source is required, a different kind of display mechanism is needed. Regardless, many lessons for ambient displays can be learned from design research in the pager field.

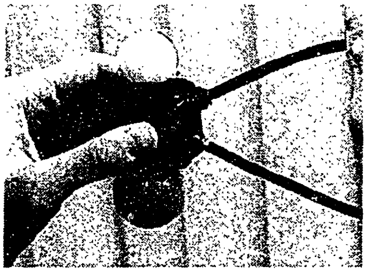


Figure 2.7
A design prototype of the Handjive haptic game system

The great technological advances made in pagers and phones have allowed researchers to consider more adventurous telecommunication devices. *Feather, Scent, Shaker* (Strong and Gaver 1996) proposed the creation of linked "shaker" objects as a means of interpersonal communication. HandJive (Fogg, Cutler, et al. 1998) introduced the idea of a pair of linked hand-held objects for playing haptic games. Philips Design has proposed the creation of many similar devices as well (Lambourne, et al, 1997). These include *Hot Badges* that signal other people about the user's interests, *Enhanced Jewelry* that integrates communication components in everyday jewelry, and *Emotional Communicators* that display the wearer's state-of-mind. However, all of these were only design sketches, and working implementations were never reached. My project shares many similar ideas as the ones above, but goes a step further and actually implements a number of the features.

2.5 wearable computing

"Every morning I decide how I will see the world that day... If I'm going to ride my bicycle, I'll want to feel the cars and trucks pressing against my back, even when they are a few hundred feet away."
-Steve Mann, describing a goal of his wearable system
in Technology Review (1999)

The personal aspect of ambient displays can learn many lessons from past and current work in Wearable Computing. People working in this field have iterated through a number of design exercises that will aid in the development of new personal devices. Also, many people in this field have already tackled some of the networking technology issues personal ambience work will face. One such project is the *Locusts* (Starner, Kirsch, and Assefa, 1998), a network of environmentally powered IR-beacons used in a messaging system. A project which considers the design of non-heads-up-display wearables is the Nomadic Radio system (Sawhney and Schmandt 1998), a speech and sound enabled wearable that uses spatialized audio and audio cues for personalized information delivery. Wearable computer researchers are also active in various issues regarding heat and the body. Starner and Maguire (1998) have even investigated the potential of using the body as a heat sink for a wearable computer.

Figure 2.8
Nomadic Radio provides a personal, wearable audio system

2.6 awareness

One of the primary directions being pursued in ambient display research is in keeping an awareness of a person or information source. Methods of maintaining awareness in computer-mediated environments is an area of widespread research. Awareness is the state of knowing about the environment in which you exist, about your surroundings, and about the presence and activities of others. Awareness is essential in collaboration to coordinate the activities in a shared workspace. Awareness support discussed in the Computer Supported Cooperative Work (CSCW) community has focused on the representation of the state of collaborators in a geographically distributed context. Technological devices such as remote cursors, multiple scroll bars, audio cues, and low-framerate video have been proposed to support the awareness of remote collaborators' activities. Dourish and Bly's Portholes project (1992) is an example of an awareness support system using low-resolution, low-framerate video.

3 conceptual issues

3.1 defining ambient display

In the race to make everything digital, the analog world has been largely cast aside. With it, all of the quality characteristics of analog displays, such as the ability to read them at a glance, have been thrown away as well. To introduce my motivation for reviving aspects of the analog world, I have made a comparison between display screens, and a new classification I have termed a *display object.*

Display screens usually reside in a single location, strive for high resolution, carry large amounts of detailed information, and can change instantly at very high refresh rates. When these attributes are fully realized, the product *demands* significant, focused attention to be useful.

Ambient displays (which are a kind of display object) are the antithesis of display screens. They are inherently low resolution, have slow refresh rates, are distributed in a 3D space, and maintain a persistent display of information. These attributes *allow* their information to be viewed in a consistent, yet, non-cognitively intensive manner.

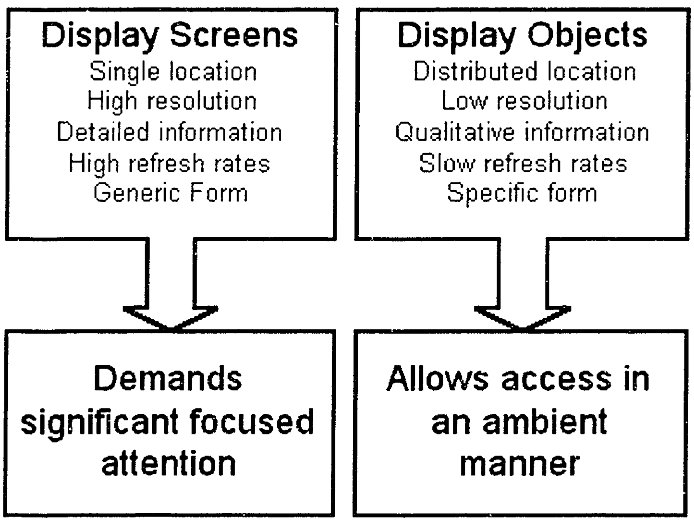


Figure 3.1
Display Screens and Display Objects have vastly different properties leading to significant differences in the applications for which they are best suited.

3.1.1 physicality

The traditional desktop computer serves efficiently as a general, customizable, malleable tool. However, its inherent flexibility and configurability can create a tension with regard to persistence of information, and the domain specificity of the information being displayed. It is an intrinsically transient information source.

In contrast, ambient displays are more domain specific. Much like a clock, they present a single source of information through a physical means in a singular, dedicated fashion. The shift here is away from the "searching" of information through a computer interface, and towards a space where you can "look" for information within your physical environment.

The very basic idea behind ambient displays is that they have a tangibility, or physicality. Physical objects are much more persistent than conventional video displays. Each ambient display, by being a separately designed object, can take a different form, allowing a user to easily differentiate between the different display objects. If several video display terminals are used, their form says little about the content being displayed, making it more difficult to quickly find the intended display. Ambient displays might also create sounds, which would be inherently spatialized in accordance with their position in a room.

The differences in the various physical ambient displays help a user differentiate the outputs; they know which device does what. The displays can simultaneously broadcast on a variety of channels throughout an environment. This is not so simple with video displays, where all the displays can transmit information in an identical, more unbounded manner. The generality, or extra degrees of freedom a video display has can sometimes cause more problems than it solves.

Furthermore, if a user is not looking almost directly at a video display, it is difficult to perceive changes, especially changes in small details of its pixels. Ambient displays have a different kind of "pixel." An example of an ambient display's "pixels" could be a physical movement, or a change in temperature, rather than color or light on a video display. Since physical objects must follow the rules of classical physics and thermodynamics, they will inherently move at slower "refresh rates" than their video terminal counterparts.

This research does not seek to replace current computer displays. However, it does aim to curb our reliance on them for a number of tasks. Leveraging off of these attributes, I believe ambient displays can bring information display to areas where a large computer display is not feasible, needed, or desired.

3.2 the design space

There are many facets to the design space ambient displays can occupy. Here, I introduce four of the central issues I encountered when creating the designs described in this thesis.

3.2.1 single user vs. multi-user

One aspect of the design space is the scale that the display is tailored to. Ambient displays can take on at least three different scales, each one providing different design challenges. The first is the personal scale, or body-space. A device could be worn on the body that transmits information in an ambient way. It could be incorporated into a person's clothing, or worn as jewelry, or kept in a pocket. The second scale is the personal area. This would include any space that is the traditional, personal domain of one person. This includes spaces like an office, a car, or a bedroom. The last scale is the multi-person space. This can range anywhere from an office meeting area to a large, public venue.

For each of these scales, there can be some modality that is more suitable than another. For an intimate, personal-scale ambient display, a designer might want to base their design on heat, vibration, or some other aspect of touch. Sound and light might not work as well for a personal display, as they are an inherently more public display media. By the same token, sound and light work particularly well for large, multi-user spaces, as they can be simultaneously perceived by many people.

3.2.2 public vs. private

Related to the single user vs. multi-user thread is the issue of privacy and sharing of information. Voice communication in general is not private by nature, as voices can be heard by others. Voice communication can become private if both people are not sharing space around them with others. Hence, the need for phone booths, and even private offices. More subtle forms of communication exist between people through the exchange of glances, or gaze, yet this is still visible, and can possibly be intercepted by others. The tactile sense presents a channel through which truly private communication can occur, even when in densely populated environments. While tactile communication might not afford the transmission of large amounts of detailed content, it is well suited to transmitting affective content.

In addition, personal information, while usually private, is sometimes needed to be shared with a larger community of people. Similarly, some kinds of information that have a general interest to a wide body of people can often be tailored to give a particular relevance to a specific individual. Tools and mechanisms must exist for moving data from the public to the private realm, and vice versa.

3.2.3 literal vs. abstract

Another aspect of the design space is the choice between the literal or abstract representation of information. While a literal choice might provide the most accurate display, an abstract interpretation still might provide the best functionality and usability. A literal representation of a data source, by definition, contains a large amount of data. The literal representation of the presence of a person might include an image of their face, the sound of their voice, and indications of their movement. In contrast, abstract representations of presence can be made that provide much less information, but are more readily accessible, usable, and aesthetically pleasing. The presence of a remote colleague might be displayed on a screen as an icon, or avatar, providing a subtle awareness of a person's availability. Choice of representation is one of the central design issues of displays in general, and takes on increasing significance with new forms of physical-digital displays.

3.2.4 local vs. distributed

Another consideration is the location of the information source a display is connected to. It is possible to be connected to information from the person sitting next to you, the people in the room next door, or collaborators half-way around the world. Each of these brings with it specific traps and needs that must be accounted for.

Communication within a shared environment is extremely high-bandwidth. Information is passed through words, actions, posture, intonation, gaze, and gesture. To transmit all of this information to a distant location is not only a troublesome technical challenge, but also a serious design issue. The challenge is so great that the local vs. distant gap might never be bridged in its literal sense. However, novel tools can be created that will bring us closer together. Some of the central issues surrounding these tools are latency, coupling, and feedback.

3.3 a perceptual perspective

Another general step to take when thinking about design is to understand the human side of the equation. By reviewing existing knowledge about the cognitive capabilities of humans, insight can be gained as to how we design communication devices and displays.

My intentions for ambient displays can be broadly broken down into two application domains: the "information overload" environment, such as a stock trading floor or a pilot's cockpit, and more "relaxed" environments, such as a person's bedroom, kitchen, or office during a non-frenzied work time. The cognitive models that are believed to be used in each of these cases are surprisingly different. In the "information overload" environment, a person tries to use *divided attention*, whereas in a "relaxed" environment, people are more concerned with *swapping attention*. In the divided attention case, the goal is to maximize the information throughput to a person. By knowing and understanding the channel capacity limitations of the human sensory system, intelligent decisions can be made concerning the choice of display. Divided attention research has clearly shown some findings that could influence an display designer's choices. For instance, it is known that when two visual stimuli are processed concurrently, there exists a capacity limit when loads get beyond a certain point. It has been strongly indicated that if the load is divided between two modalities, performance is better than when everything is in the same modality (Pashler, 1998). Even further, many aspects of what makes a task easy or hard to process concurrently with divided attention have been researched and are known (including details about relative spatial arrangement, color, and size) (Pashler, 1998).

There is a lot less known about "relaxed" situations, and attention swapping. Harold Pashler of UCSD writes, *"In short, the set that people adopt in many routine activities is much more nebulous than what is demanded by a typical discrete laboratory task."* However, some basic findings that can help the design of ambient displays are known. For example, some research has shown that people pick up the "gist" of a scene based on a parallel analysis (limited by poor acuity for more peripheral objects) and direct subsequent fixations to objects that either fit with, or conflict with this "gist" (Pashler, 1998). For these "relaxed" environments, ambient displays should allow people to easily and quickly shift their focus of attention between displays without breaking the mental continuity that person has in the environment.

I believe that considering perceptual issues like these from the outset of a design is vital. Keeping the design space in mind allows the designer to think about tailoring the display to the content of the information, while keeping the perceptual perspective in mind forces the designer to think about the end user.

4 ambient displays

Over time, specific prototypes arose to illustrate the notion of ambience. These received the name *Ambient Displays*. Ambient Displays are physical devices that can transmit information, often in the background, or periphery, of a person's attention (Wisneski, Ishii, Dahley, et al, 1998). Whereas the computer screen requires constant, focused attention in order to be functional, ambient displays do not. A person can check the state of a display by glancing around the room, or keep a consistent awareness of a display in the background of their attention. The creation of the ambientROOM and two ambient displays, the Water Lamp and Pinwheels, have served as testbeds for developing the ideas of ambience.

My work on ambience is distinguished by its emphasis on the physicality, or tangibility, of the display. The physical nature of the devices lends an inherent multi-modality to the displays, as they move in 3D space and give off sound during intensive use. I believe this physicality is a crucial design element of ambience.

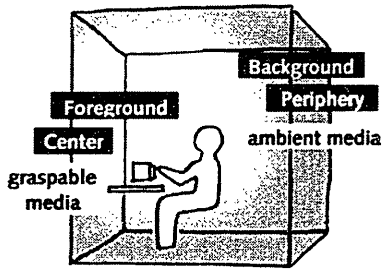


Figure 4.1
A design sketch of the ambientROOM indicating the co-existence of graspable and ambient media

4.1 ambientROOM

The early steps in developing these ideals began with work on the ambientROOM (Ishii, Wisneski, et al, 1998). The ambientROOM surrounds the user within an augmented environment by providing subtle, cognitively background augmentations to activities conducted within the room. In this environment, the use of sound, light and shadow as ambient displays was explored. Specifically, displays such as water ripples on a ceiling, abstract spots projected onto a wall ("Active Wallpaper"), and various ambient sounds were created.

By the nature of its size and design, the space of the ambientROOM is specifically tailored to be a single-user environment. After a round of prototyping displays for this situation, a decision was made to create displays that could be multi-user, more flexible, and used in larger spaces.

This led to the development of two standalone, portable ambient displays: the Water Lamp and Pinwheels (Dahley, Ishii, Wisneski, 1998). The Water Lamp is an extension of the ceiling water ripples of the ambientROOM and the Pinwheels explore the ideas of physical movement caused by invisible information flow. Both are designed on the metaphor, as in the ambientROOM, of natural physical phenomena.

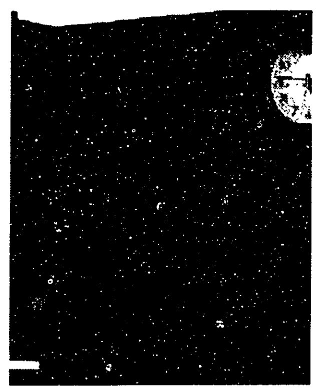


Figure 4.2
Active Wallpaper indicates the presence and activity of people in a distant place

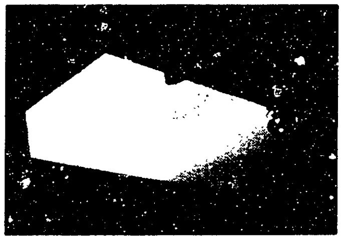


Figure 4.3
Above: Water Ripples on the ceiling of the ambientROOM reflect the presence of a loved one

Left: an outside view of the ambientROOM

4.2 water lamp

The first display created was the Water Lamp. Water ripples created by raindrops on the surface of still water was the inspiration behind the Water Lamp design. Instead of physical raindrops, it was imagined that "bits," or digital information, falling from cyberspace could create physical water ripples, resulting in a soothing display.

With this device, a light shines upward through a pan of water, which is actuated by changing information. This action produces changing patterns of light projected onto the ceiling of a room.

The Water Lamp is composed of a wooden base, 3 aluminum support tubes and an acrylic tray filled with oil (the first prototype used water in the tray, hence, the name "Water Lamp," however, it was found that oil has a more consistent rippling action, does not evaporate, and left no residue over time). The actuating mechanism of the Water Lamp consists of an off-axis weight mounted on a DC motor. The wobbling of this mass as the motor rotates causes a subsequent wobbling of the lamp itself, which causes concentric rippling patterns in the lamp's oil. The speed of the motor is adjusted so that the frequency of the wobbling is approximately equal to the resonance frequency of the lamp, thus amplifying the motion of the rotating weight.

The motor is controlled by a PIC-based embedded control system. The PIC implements a serial server to permit control by a computer through a serial interface. The computer specifies the actuation duration of the motor through ASCII values sent to the PIC. Producing different amplitudes of ripples in the oil bath required experimentation to find the combinations of pulse duration and frequency that generate a desired effect.

Figure 4.4
The Water Lamp throws shadows of activity on the ceiling

4.3 pinwheels

The next display created was a set of pinwheels that could be computer controlled. The Pinwheels evolved from the idea of using airflow in the ambientROOM. I discovered that the flow of air itself was difficult to control and therefore, difficult as a means of conveying information. As an alternative, it was envisioned that a visual/physical representation of airflow based on the spinning of pinwheels could be legible and poetic. The Pinwheels spin at different speeds based upon their input information source.

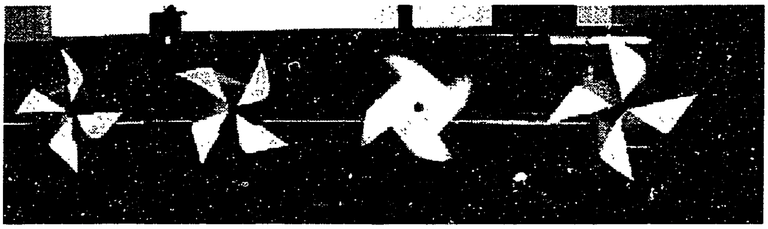


Figure 4.5
The Pinwheels deployed in a Media Lab common-area

The Pinwheels are made from folded fiberglass. They are powered by standard brushed DC motors with integral tachometers coupled to the drive shafts. Each motor is controlled by a motor driver unit, which may be daisy-chained to allow for multiple pinwheel configurations. Pulse width modulation controls the speed at which the motors spin. At one end of the pinwheel bus is an interface unit to the computer whose host application controls the speed of the pinwheels. The core of the interface unit is a PIC microcontroller, which implements a serial server that responds to commands from the computer for loading the shift registers with new values and for querying their current values.

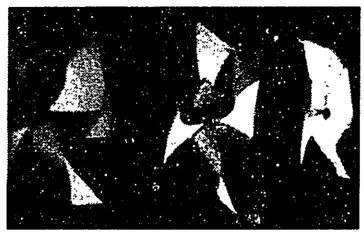


Figure 4.6
The Pinwheels rotation reflects changing online information

4.4 application areas

As introduced in Chapter 3, there are two general kinds of environments that have been considered in creating ambient displays. The first is the "Information Overload" environment, where there is a clear focus on productivity and task completion. In this kind of environment, displays are created and designed with a goal to maximize information flow. The aim is to present information in the periphery of a person's attention in a non-intrusive manner. Displays like these are being used now in places like stock trading houses. Often, stock traders who work in an office (not on the trading floor) pipe in the sound of the trading floor into their environment. By persistently, peripherally listening to the hum of the floor, they can be kept aware of the market's general state. This ambient display helps them maximize their productivity. However, more and more trading is being conducted electronically. For electronic transactions, there is no sound created. A heavy volume of electronic trading does not make noise. Some other kind of peripheral display is needed.

Other situations similar to this "information overload" environment include airplane cockpits and car interiors. I believe that ambient displays can be of use in any information-intensive situation where a constant awareness of many information sources is vital.

The second kind of environment this work is aimed towards is a more common, everyday kind of situation. Locations could include a person's bedroom, kitchen, or office during a non-frenzied work time. In this situation, the primary focus of using an ambient display is to be able to be connected to information without being near a computer screen. This is essentially an argument based on the belief that humans do not want to have terminals placed in every room in their homes. Instead, I believe that people would find it comfortable and aesthetically pleasing to have physically-based information fixtures present instead. These types of ambient displays could be used in a wide variety of settings, including the awareness of a baby or child, the coming of an impending event, such as a meeting, or the awareness of simple changes in a day's weather for those not close to windows.

The ambient display devices created for these environments all exist as objects, or spaces in a room. As a result, information that needs to be kept private, or other kinds of personal information in general, might not be well suited to display on these devices. After completion of these prototypes, I concluded that this personal scale was a ripe area for exploration.

5 personal ambient displays

The primary focus of this thesis concerns ambient displays on a personal scale, or *personal ambient displays*. This area of work closely builds on previous work in Ambient Displays, but changes the focus away from devices being distributed in an architectural space, and moves towards creating ambient devices that can take on a more personal, or intimate role while being worn or carried near the body.

To research this area of devices, I have created a group of small, wireless objects that can warm up and cool down or dynamically shake and shift. These devices can be used as physical display devices, worn on or near a person's body. Further, I have created a system that allows for user reconfiguration of each display, such that specific information sources can be mapped to different tactile modalities. Designing these effectively requires an understanding of how sensitive we are to heat and other physical stimulus and careful consideration of latency issues in dealing with physical phenomena. Answers to some of these issues have been reached through prototyping, implementation, and by monitoring user reactions. This chapter details the design, development, and technology of my personal ambient displays.

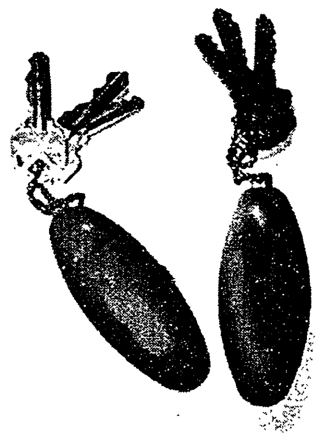


Figure 5.1
A mock-up of a keychain Personal Ambient Display

5.1 vibration (output)

One of the most familiar tactile display mechanisms used today is the pager vibrator. As such, this was a practical place to start my interface exploration.

When a pager vibrates, a person will usually grab the pager and look at its LCD screen to get more information about who called, or sometimes get some other kind of data (like network outage reports for network administrators, or sports scores for avid sports fans). Many people prefer to have a vibrating pager, rather than one that makes noise, so that they, and the people around them, are not interrupted each time a signal is sent. They can easily ignore its signal if they so choose.

My goal was to see if I could create an object that could shake or vibrate at variable strengths or frequencies, such that if an extremely important message arrived, the object would really catch a person's attention. Likewise, if the message received was not extremely vital, it could convey that through its only slight movement.

A second avenue I wanted to explore was the prospect of having a device that could move or shake in a more persistent manner, so that it could be used to display continuous information rather than discrete events. The main challenge here is to make the object comfortable to the user, and not just a major source of annoyance.

5.1.1 scenario

Given this functionality, a personal ambient display could be created that would keep a person abreast of an information source. For instance, it could be linked to a group's electronic calendar and serve as a schedule reminder. The calendar, which knows about a person's appointments, could communicate with the display to give a "nudge" when an appointment draws near. Fifteen minutes before a scheduled meeting, the device could gently shift its weight, providing a subtle cue as to the impending meeting. As the meeting draws to within a few minutes of realization, and as people start to gather, the device could more actively alert the user to the appointment by vigorously shaking.

5.1.2 implementation

The realization of these personal ambient displays required design and engineering on both the hardware and software ends. Each object basically consists of four basic classes of components:

- Circuitry controlling the display mechanism
- A battery or power supply
- An RF transmitter and receiver for communication
- A microcontroller for overall control of the device

A later section on System Architecture (5.8) will describe the overall implementation of the devices. This section will detail aspects of how this particular "shake" display mechanism was realized.

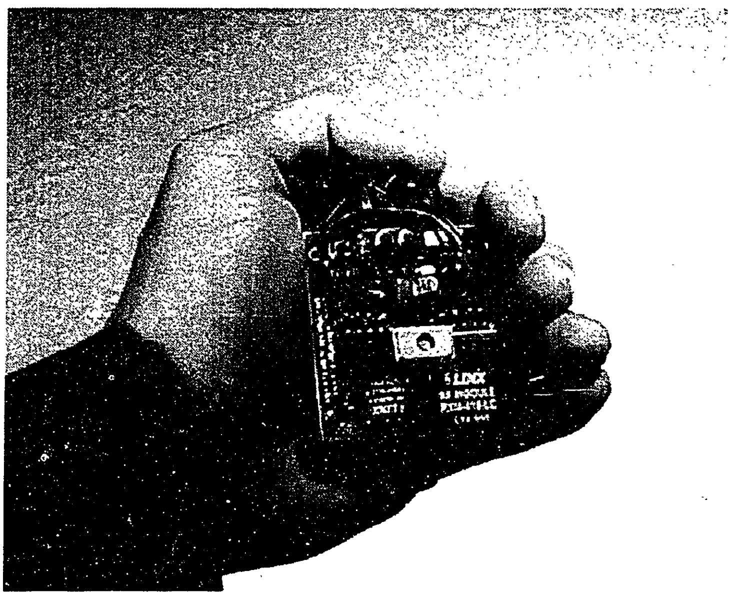


Figure 5.2
The "Shaker" personal ambient display

To create a vibrating object, standard pager motors were used. These motors spin a small, off-axis weight at a high rate of speed to create the vibration effect. Pulse width modulation controls the speed of the motor as determined by the microcontroller.

Using standard pager motors created a vibrating, or buzzing, of the object. The first thing I noticed was that it was very hard to distinguish between the pager motor being minimally driven and driven at maximum speed. The same kind of buzzing-feeling was left either way. Even with speed control, it still felt like the "on/off" effect pagers typically have. It left the impression of an event-driven display.

As an alternative, I started experimenting with larger off-center weights. An easy way to do this was to simply attach a metal rod to the rotating motor. This design makes the object's center of mass actually change as the motor spins, leaving a feeling as if the object is shifting, or shaking, instead of vibrating. With this design, it was easy to distinguish whether the object was being shaken softly or vigorously. Instead of discrete events, it was possible to map continuously changing information to this display. However, the inclusion of the relatively large rod made the overall object size much bigger. A similar effect might be possible by using a smaller radius, yet heavy and dense off-center weight made of lead of some similar material.

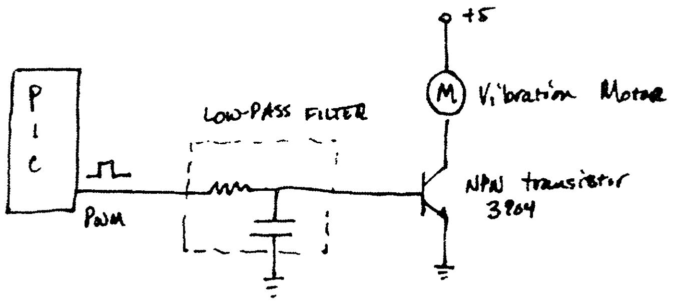


Figure 5.4 *Circuit diagram for the "Shaker" actuator*

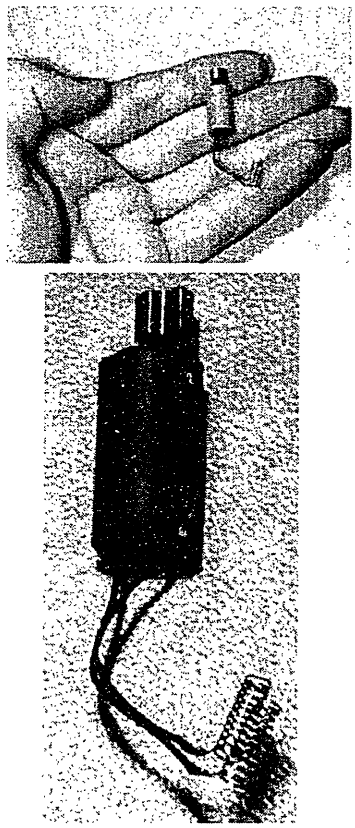


Figure 5.3
A pager motor: an off-center weight quickly rotates around a center shaft

5.2 heating and cooling (output)

After experimenting with vibration, shifting, and motion, I had the desire to explore a mechanism that would allow for more continuous display, rather than one with an "on/off" feel to it. Temperature modulation was chosen to provide that functionality.

5.2.1 scenario

One of the most popular and personalizable information sources on the internet is stock portfolio performance. It is possible to watch the performance of a stock over the course of a day on a computer screen, and it is also possible to get paged when a stock crosses a predetermined threshold. However, to keep in touch with stock information in a more persistent way, a personal ambient display can be used. A trader's display could vary in temperature depending on fluctuations in their stocks, warning the trader when extremely wild swings occur, and providing a subtle, background awareness of activity most of the time.

This information would be well suited to the back of a person's watch. With this *StockWatch*, the back of a watch becomes a display, complementing the display on the front. During the course of a day, if a person's stock portfolio approaches a high threshold, the watch will warm up. If it starts to approach a low threshold, it will cool down.

5.2.2 implementation

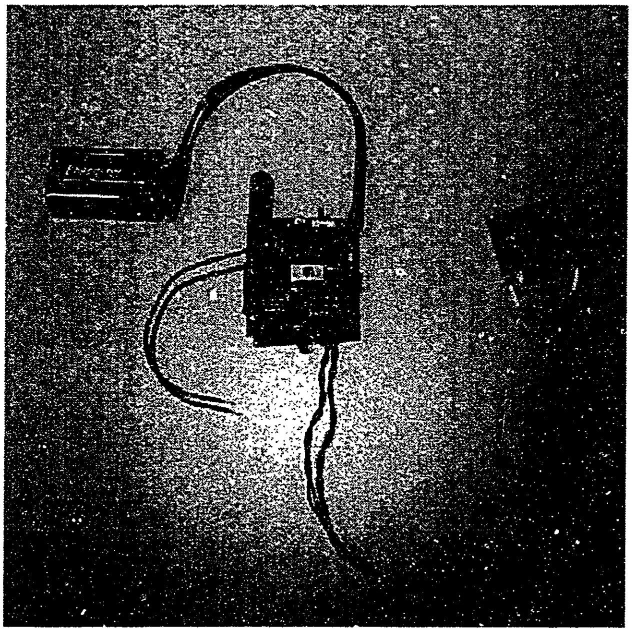


Figure 5.5
A "Touch/Heat" Personal Ambient Display including a battery, peltier junction, and wire for touch-sensing

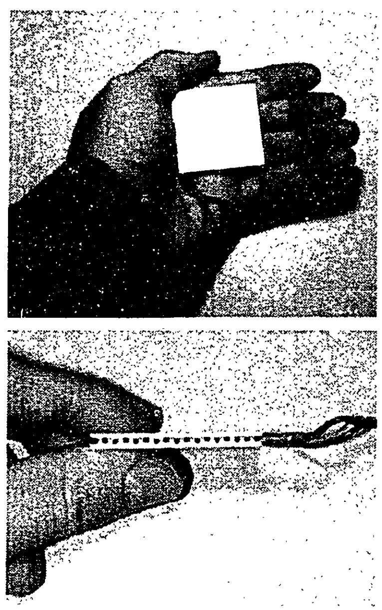


Figure 5.6
The front and side of a peltier junction

To make objects hot and cold, I used peltier junctions. Peltier junctions (or thermoelectric heat pumps) are devices that can get cold on one side and hot on the other. By passing a DC current through semiconductor junctions assembled between, and bonded to, two ceramic plates, heat is "pumped" from the cold side to the hot side. Reversing the direction of the current flow changes the "hot" side to the "cold" side. Through regulating power to the module, precise temperature control can be achieved.

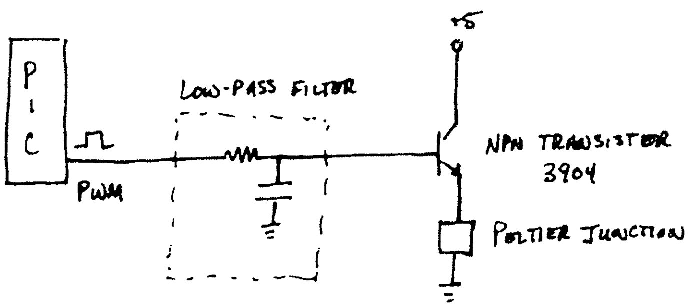


Figure 5.7 *Circuit diagram of the "Heat" actuator*

The main technical issue surrounding the use of heat as a display medium is power concerns. Making a device hot or cold requires a lot of power. In my implementations, I powered the devices with a single, standard 9-volt battery. Under intensive, constant use, battery life is only on the order of 4 hours. Using resistive heating is a viable alternative, but less attractive, as it can only create heat, whereas peltier junction also provides the sensation of cold. However, resistive heating could consume less current (further consideration of this topic can be found in section 5.8.4. Hardware Design).

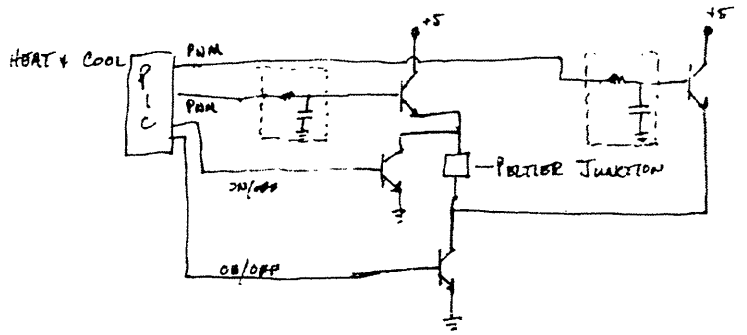


Figure 5.8
Circuit diagram of a peltier junction circuit that can reverse its current, making it possible for the same surface to flip from hot to cold

5.3 data sources (input)

To complete the input end of the StockWatch scenario, I needed to retrieve information from an online source, and route it in the appropriate way to the personal ambient display. In this case, I needed real-time stock information to govern the temperature of my display.

To get this information, a stock-tracker program was written that allows the user to set the stock to be tracked, the high/low thresholds for the stock's value as well as the high/low thresholds for the stock's volume. The application also allows the user to specify how frequently the stock price is updated from the internet (e.g. every 10 seconds or 5 minutes).

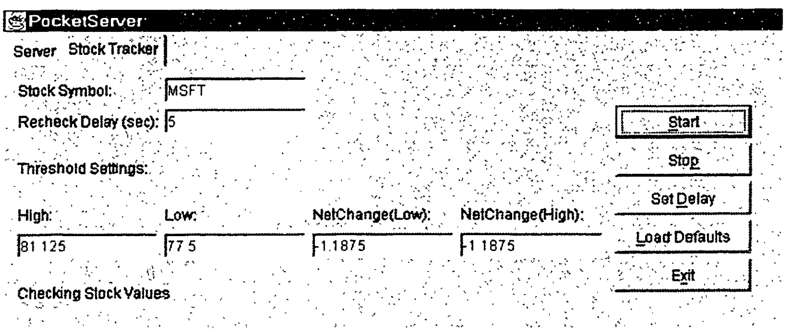


Figure 5.9
The StockTracker can show you yesterday's default values for a specified stock, and then let you choose today's thresholds

The program is written in Java, and incorporated into a larger scheme of use and reconfiguration of personal ambient displays.

5.4 use and reconfiguration

I imagine that a person would not totally dedicate a particular display for a specific information source. For instance, a person might not always want stock information on their watch-display, but rather, might want to use it as a calendar reminder. If a person has access to these and other data sources, a mapping and reconfiguration system must exist.

For personal ambient displays, two configuration and mapping systems have been used. One, the *PocketServer* system, was built specifically for this research project, and the other, *Hive* (Gray, 1999), is part of a larger effort to make a standard networked-device connection system.

Both systems have a similar interaction technique. Through a GUI, a user can see icons representing specific physical displays and information sources in a window. By clicking and dragging the mouse between two icons, a connection can be made. Similarly, by dragging an arrow from an information source to a display, that source can be mapped to that display. Both of these architectures are generalizable to the current ambient displays that exist, and will be flexible to the addition of more sources and displays for the future, allowing an infrastructure for further research.

5.4.1 pocketserver

The PocketServer is a custom-built connection package specifically made for reconfiguring and communicating with personal ambient displays. The PocketServer sends state change messages to the displays and also sends data from online/networked sources. Through its GUI, it can create and re-route data connections to specify where and how data should be delivered.

There are two kinds of modes the devices can operate under. In the first, a device is connected to an online data source. In this case, data streams from a computer (or similar base station) directly to the device. Devices are also capable of is being connected directly to another device. Each device keeps its own connection list, so that *Device A* can be directly connected to *Device B*. In this case, the PocketServer sends out "state-change" messages whenever a configuration is changed. To reconfigure a community of devices, they must be near a computer. Other than the reconfiguration need, devices can operate independently by talking peer-to-peer.

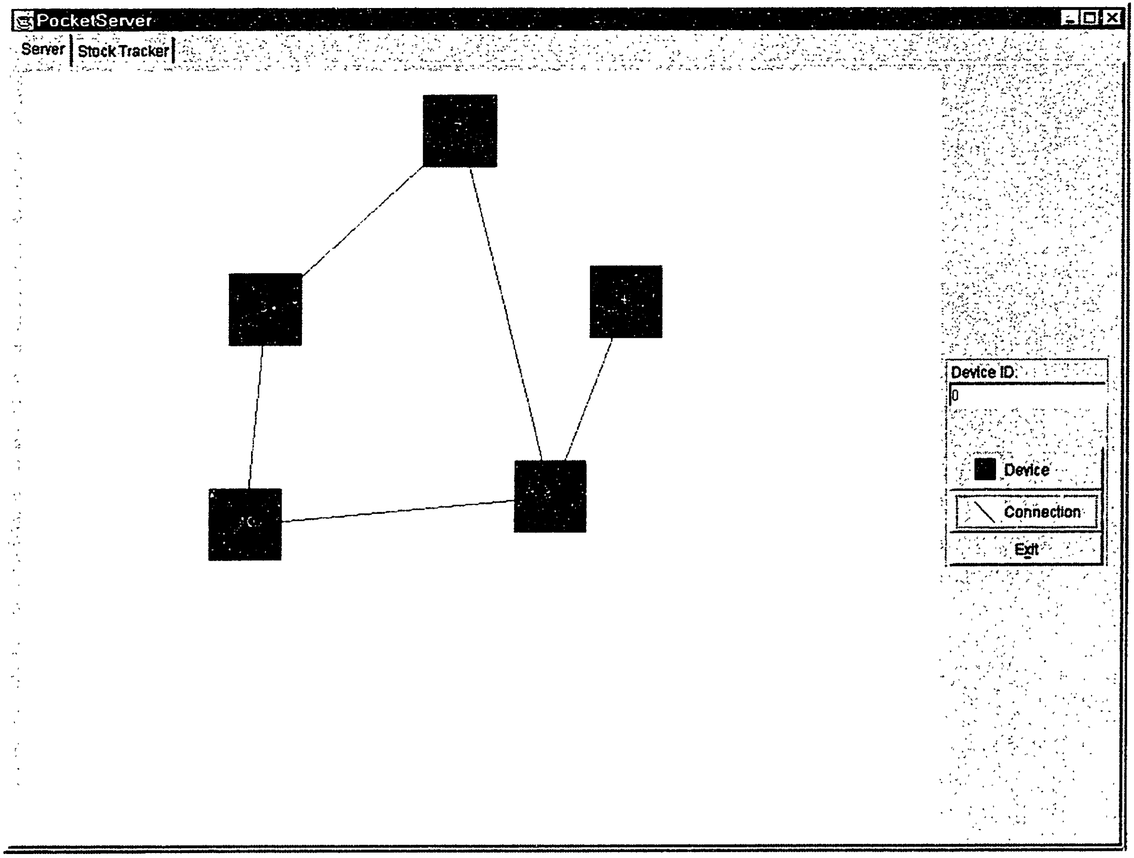


Figure 5.10 *A connection network of 5 different devices on the PocketServer GUI*

5.4.2 hive

The Hive infrastructure (created by Minar, Gray, & Roup) was used with personal ambient displays as well (Hive, 1999). The Hive system is an ongoing research project in the MIT Media Lab that implements a connection mechanism for things and information sources, much like the PocketServer. However, Hive is fully networked, such that a "Hive-cell" running in one room can talk to a Hive-cell running on a different floor of a building, or even a more distant location (PocketServer did not reach this level of network capability. It only runs on one computer).

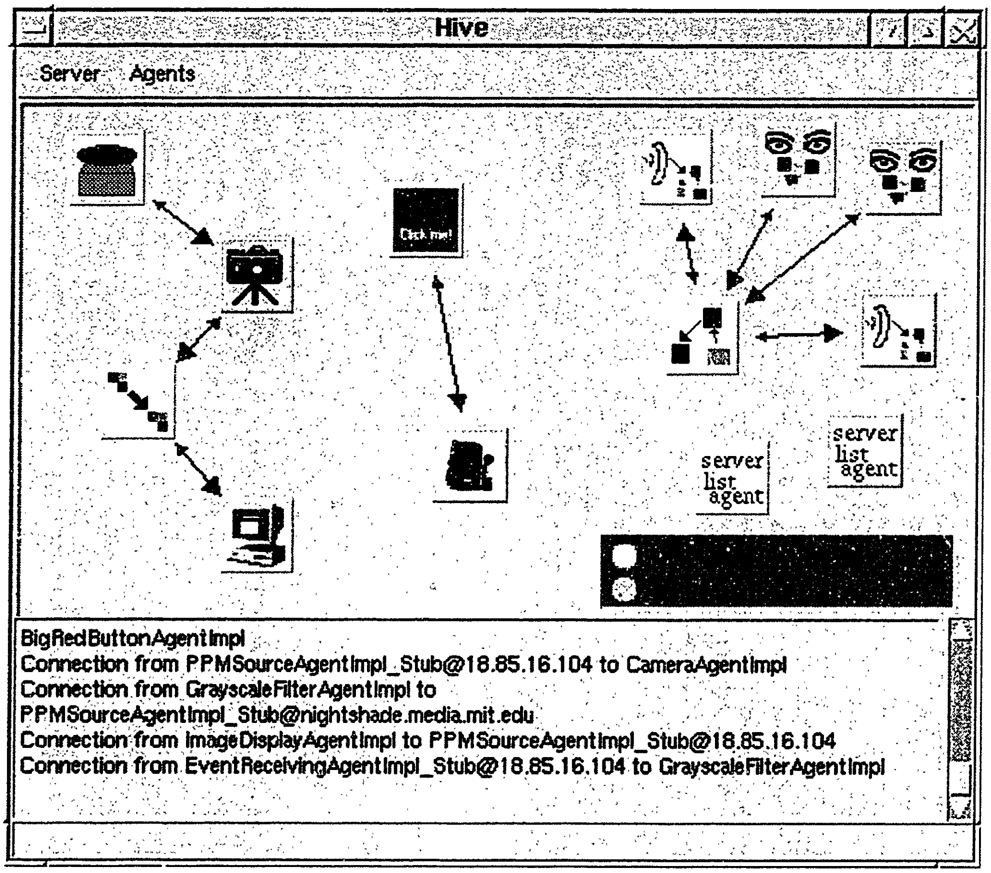


Figure 5.11 *A complex connection network of Hive objects and agents*

All of the personal ambient displays I created are accessible and manipulable through Hive. In addition, the StockTracker data source used for this project was turned into a Hive source as well, such that other researchers could connect stock information to different projects.

The benefit of making these displays "hive-objects" is that Hive is a common infrastructure for other input and output sources around this research lab. If another researcher created a suitable data source, and made it accessible though Hive, I can connect it to a personal ambient display by simply clicking and dragging. This did occur, as I was able to connect a "warming" device up to a web-hit monitor written by Nelson Minar, a fellow researcher. Whenever a person would access a web page in the Media Lab domain, an event would be sent to a personal ambient display. The resulting effect was that the display would warm up when traffic on the Media Lab's site was heavy, and remain room temperature when traffic was slow. Hive allows serendipitous connections like this to be both simple and fast.

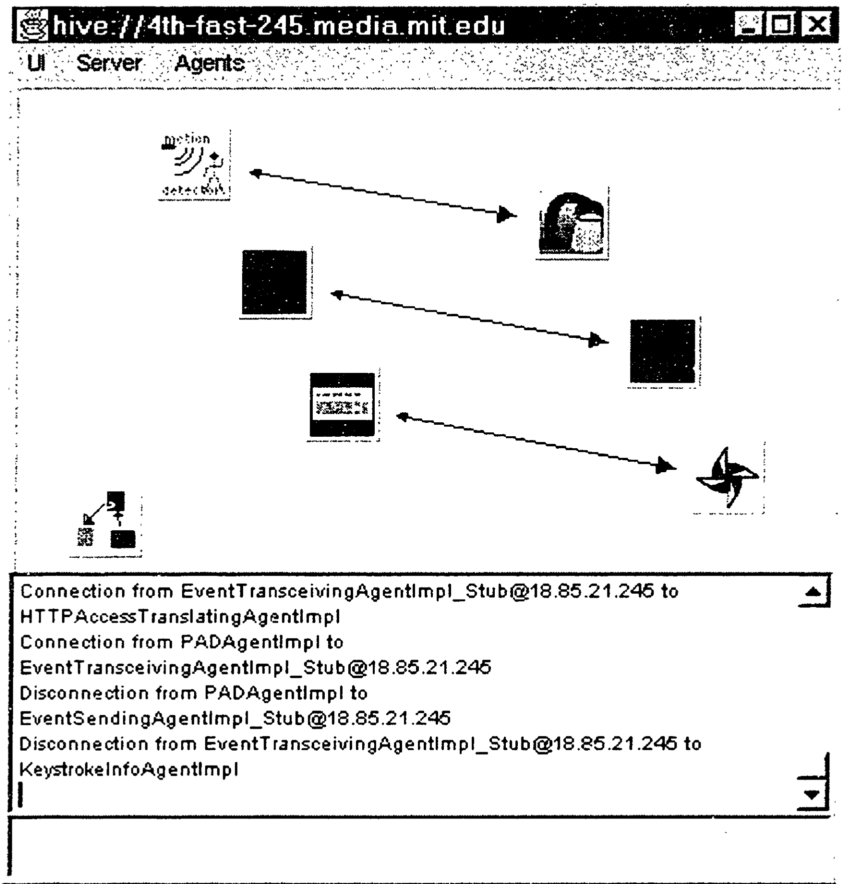


Figure 5.12
A Hive configuration where a motion-detector is connected to a lamp, a web-traffic-monitor is connected to a personal ambient display, and a keyboard-stroke-monitor is connected to the Pinwheels

5.4.3 tangible alternatives

All of the connection mechanisms implemented for this project require a GUI. However, tangible reconfiguration approaches are worth considering as well. For instance, there could be certain objects, or physical icons, that represent specific data sources. By touching a personal ambient display to a physical icon, a connection can be made. This feature is desirable, but has not yet been implemented.

Considering a physically-based reconfiguration scheme led me to think not only about connecting objects to data sources, but instead, about connecting objects to other objects.

5.5 a different approach: object to object

Connecting personal ambient displays to one another, instead of online information sources, was my next area of investigation. By adding simple input mechanisms to personal ambient displays, aspects of contextual awareness and simple, tactile messaging could be investigated.

To accomplish this task, the devices must posses the ability to communicate with one another. One option is to have two devices "hardwired" to each other, such that manipulating one of them will always effect the other. Two objects can be thought of as being synchronized. Another option is to use the reconfiguration systems already created to make networks of devices. Both of these options were implemented.

The first thing to consider is what kind of "input" should these objects support. Rather than opting for complex, button and screen-based interactions like those presently found on phones, pagers, and personal-digital-assistants, I decided to focus on simple, physically-based input interactions.

I have made two different combinations of objects:

- When one object is shaken, the other shakes as well
- When one object is touched, the other object heats up

The first combination is a direct mapping: shaking one end leads to shaking on the other end. The second input/output combination is on a slightly higher level. The intention is to transmit the "warmth of touch" over a distance, through two common objects. In both cases the effect is that the objects are synchronized. The shaking is a direct synchronization, but the warmth is a causal synchronization. Another example of causal synchronization is if one object is squeezed, another would expand. Users of objects with direct synchronization might have a tendency to fight over the state of the object, as informally evidenced in projects like the inTouch and HandJive. I believe that with causal synchronization, users will be more receptive to thinking about the objects in terms of input and output, creating a clearer communication channel. To explore ideas like this, these two scenarios were implemented.

5.6 shaking (input)

The movement, or shaking, of an object was the first physical input mechanism implemented. It was added to the personal ambient displays that used shaking and vibration as an output display.

5.6.1 scenario

By keeping track of how a personal ambient display is being shaken or moved about, a surprisingly large amount of contextual awareness can be inferred. For instance, a personal ambient display of this type in a person's pocket can passively get some simple notion of whether or not a person is walking, moving, or at rest. This information can be relayed to another corresponding display, expressing clues to the other person's physical state. The simplest way to imagine this scenario is to think of a parent wanting to keep an awareness of a toddler. These could be used as a warning mechanism for situations where a child is moving when they should not be. However, I imagine a more common use would be for parents to just keep a consistent, peripheral awareness that their child is up, active, and in motion, providing a consistent emotional link to a child when far away.

5.6.2 implementation

Detecting the movement, or shaking, of an object is done in this case through the use of an accelerometer. The specific accelerometer I used (the Analog Devices ADXL202) can detect dynamic acceleration of up to 2 G's along 2 separate axis. It is also relatively low-power, allowing battery powered motion sensing.

The biggest problem encountered with the shaking input was in looking at the signal generated by the accelerometer and recognizing when a person was actively shaking the object, or just rotating it around its various axes, changing the gravitational direction. For this implementation, I only looked at areas of activation above 1 G, taking care of this problem. However, there could be more complex methods that would allow gravity to be filtered out so that shaking movement below 1 G would be detected, but still distinguishable from noise.

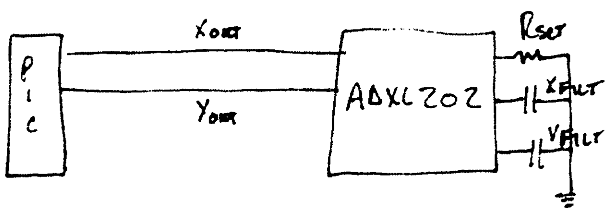


Figure 5.13
Circuit diagram for the accelerometer sensor

5.6.3 connections

These "shaker" objects were integrated into the two connection mechanisms, such that you could connect an information source to an object, or you could connect two objects together. When connected together, one object vibrates with a strength proportional to the strength the other is being shaken. A hard shake on one end translates into a hard shake on the other, just as a soft shake results in another soft shake. Also, networks of objects could be made, such that shaking one object sends a signal to many listeners.

The shaker objects were somewhat successful. The biggest problem encountered was with latency. If there was a perceptible delay between the time one person shook an object and the time the other responded, people lost the sense of connection and causality. (This issue is taken up further in Discussion section 6.2).

5.7 touch (input)

The next input interaction that was implemented was a touch sensor. The goal was to determine exactly when an object was being touched by human skin. This mechanism, coupled with the output mechanism of heat, creates the ability to send the "warmth of touch" over a distance.

5.7.1 scenario

Heat, specifically body-heat, has long been associated with the notion of presence. I believe that a simple messaging system that transmits an idea of presence can be effectively made with the touch-heat combination of personal ambient display. It is easiest to think about this as being a piece of jewelry, much like the heart necklaces (popular among young girls) where a heart is split down the middle, with each person wearing half. These heart necklaces are usually worn by best friends, and signifies a bond. In this scenario, you can imagine that each half of that piece of jewelry remains linked, such that when one person touches their half with their hand, the other warms up.

5.7.2 implementation

This combination has been created, although, not in a size that would allow it to be made into comfortable jewelry. The touch sensing implemented is based on a method suggested by Rehmi Post (found in Baxter, 1997).

The touch sensing is created through capacitive sensing. Skin contact with an electrode can be sensed by measuring the increase in the electrode's total capacitance. This is a simple, elegant method, well known in common applications such as in touch-sensitive elevator buttons. It can be implemented with a single bi-directional digital I/O pin on the microcontroller, and a single leakage resistor. This method is also very robust and worked extremely well in this implementation.

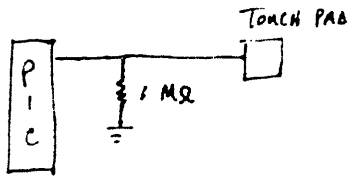


Figure 5.14
Circuit diagram for the touch sensor

The microcontroller can sense whenever skin touches the electrode, which can be any kind of conductive surface. By using conductive parts in the packaging, or by using conductive paint, "hot-spots" can be created on an object that will sense touch. This has the potential to be a very powerful interface technology, as objects can now have a knowledge of when a person is going to interact with it. An object might stay "powered-down" or passive to some extent until it recognizes that it is being acted upon.

5.8 system architecture

This section details the overall architecture and technical design of the whole system, concentrating on the communication mechanisms used between devices and computers in this implementation.

5.8.1 potential architectures

There are three different potential architectures whereby a system like personal ambient displays might be feasible.

The first architecture is similar to existing portable phone and pager networks. Each device could talk directly to a base-station located somewhere within the vicinity of a few miles. The routing of messages and data could be done through similar ways as with pagers. This architecture might be easiest, as the infrastructure already exists to support this kind of messaging. However, device size and power limitations created by the need to send data such a large distance could be very restrictive.

Figure 5.15
In the first architecture, a person's devices all talk individually to far away base stations, like cellular or radio towers. Signals must travel a few miles or more.

* *Figures 5.15, 5.16, and 5.17 are inspired by, and modified from the Bluetooth consortium's web site: http://www.bluetooth.com*

A second architecture is the polar opposite as the first. In this method, each personal device on or around a person's body would communicate with that person's wearable computer, which would have a connection through a cellular, or wireless network of some sort. In this kind of "body-net" the signals from each individual device a person uses only have to travel a few feet. This allows devices to be very small and low-power. However, this method still necessitates the need for a person to have at least one device capable of long-range transmission on their body.

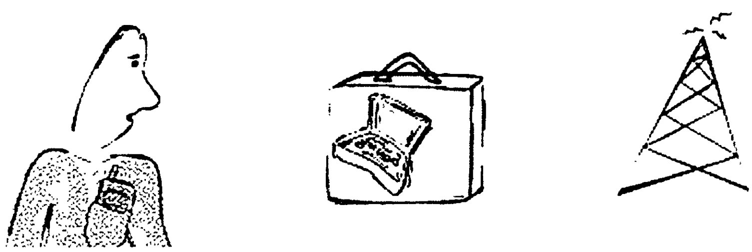


Figure 5.16
In the second architecture, a person's devices all talk to their wearable computer. Signals only have to travel a few feet.

The third architecture is the one I settled on to implement. In this method, each device uses local RF signals (on the order of a 20 meter range) to talk to other devices in the vicinity, other computers, repeaters, or small base-stations. Each room of an office or a house could have a small node somewhere in the room that serves to listen for, and transmit messages. The biggest limitation on this method is that it does not extend to outdoor use, or use in "un-wired" locations very well. However, for prototype implementations of the system, this was the most feasible route to follow.

Figure 5.17
In the third architecture, devices talk to local base stations (like computers or repeaters) within rooms. Signals have to travel about 20 meters.

Industry trends are leading towards a technology infrastructure that would make the implementation of personal ambient displays, and small devices like it, possible. The Bluetooth standard is at the forefront of this effort. This group of companies is trying to make a standardized open protocol solution for low-cost, short-range wireless communication. Jini, a project of Sun, addresses many of the software issues I encountered. Jini technology provides simple mechanisms that allow for the connection and removal of physical devices from networks and communities. If both of these efforts are successful, devices like personal ambient displays will come closer to feasible implementations.

5.8.2 technical detail

The realization of these personal ambient displays required design and engineering on both the hardware and software ends. The basic design of the system is to attach an RF transmitter and receiver to each of the displays, and to attach a RF hub transmitter/receiver to the serial port of a server computer. The server is used to send state change messages to the displays and to send data from online/networked display sources to the objects. The server is also used to determine which displays are connected to which other displays, and to debug the operation of the displays during prototyping.

The software design was broken up into 4 modules. The first is the graphical user interface (GUI) for connecting devices, adding devices, and setting properties of devices on the server. Next is the RF serial interface and protocol, which allows the server to receive the RF signals coming from the devices and transmit the RF signals to the devices. Third is the microcode on the devices for controlling the RF, monitoring inputs, and generating outputs. The final module is dynamic information mapping, which involves being able to hook up continuous information sources from the Internet (i.e. stock prices, network traffic, etc.) to the inputs of the display objects.

The hardware design involved 3 stages of development. In stage one, different components were tested to determine which best met the design criteria, size restraints, range requirements, etc. During stage two, solderless breadboards were used to prototype multiple different revisions of displays. Finally, in stage three, printed circuit boards were created for the different types of devices (server, touch/heat, shake/vibrate).

5.8.3 software design

Server and Graphical User Interface

The server and GUI were developed in Java. There are three main reasons that Java was chosen. First, I wanted the project to be easily portable. It has been developed for primary use under Windows NT, but for the future, I wanted to be able to easily port to UNIX. The second reason for using Java is that it makes communication via the serial port easy to implement, albeit slow. Finally, Java was chosen so that the code could essentially just be cut and pasted into Hive.

The basic design and implementation of the GUI involved writing code for displaying devices and connections between devices on the main field of the application. Adding, deleting, moving, connecting, and changing properties of devices are the main operations that were implemented. The final implementation allows a user to set a device with a given device ID onto the connection screen, and then draw lines between devices to connect and disconnect them from each other. Given more time, work would be done to make the GUI much more aesthetically pleasing.

The online information sources are modeled in the software architecture as devices that take no input and only generate outputs. The first external information source that was designed and implemented for these prototypes was a stock market tracker. This stock tracker exists in the same Java application as the server GUI. It allows the user to set the stock to be tracked, the high/low thresholds for the stock's value as well as the volume high/low thresholds. The application also allows the user to set how frequently the stock price is updated from the internet. At the designated time interval, the application fetches the stock price, checks to see if the new price crosses any of the user-defined thresholds, then, if it does, it calculates the correct activation level and sends the connected devices an activation packet with the corresponding activation level. Otherwise, if none of the stocks cross any of the thresholds, the program does nothing and waits until the next interval to poll the stock price.

Data Protocol

Probably the most time consuming piece of the software development and the most hardware dependent software module was the RF serial protocol. The final devices used Linx LC-Series RF transmitter/receiver pairs. Much time during the software development phase was spent on determining how to interface these components and their timing constraints. In the end, the protocol sent 8-bit interval packets at 4800 serial baud rate and achieved approximately half of the baud rate in bandwidth. Here is what a standard packet looks like (all bytes are 8-bits long):

1: Start Byte	2: Command	3: Device ID	4: Data	5: Checksum	6: Stop Byte

Figure 5.18: *Breakdown of a serial RF packet for the personal ambient displays.*

The first byte is used as a signal for the start of the packet. The devices listen for this byte constant (0xFF00) when polling the RF. Using this start byte eliminates the worry of picking up packets in the middle of transmission. If a device hears a byte other than the start byte, it simply throws the packet away, timeouts for a predetermined amount of time and begins listening again.

The second byte is used to tell the devices what kind of packet it is receiving. For instance, there are commands that tell devices to turn on their actuators, while others tell devices to add and delete devices from specified device connection lists.

The third byte is simply the ID of the individual device. Each device ID is unique, and different ID ranges indicated different device types. For instance, in these implementations, ID's in the range of 0-10 are shake/vibrate devices, while 240-255 are server and repeater devices. Device ID's are necessary to implement the connection methods. Each device holds its own connection list in RAM and adds and deletes devices from the list on demand from the server. When receiving a packet, each device checks whether or not the sender of the packet is in the receiving device's connection list. If it is, it performs the command using the data from byte 4, otherwise it ignores the packet and goes back to listening for new packets.

As mentioned above, byte 4 is used to supply an argument to the command byte. For instance if a packet is sent with the second byte equal to ACTIVATE, byte 4 would contain the activation level (0-255).

The fifth byte contains the parity checksum for the packet. The parity checksum is very simple to implement and data correction checking is not imperative to the operation of the devices. Those are the main reasons that parity, and not CRC, was chosen as the checksum protocol. To calculate the packets' parity checksum, a procedure walked through all the bits in the different bytes of the packet and added up the number of bits that were set to one. This is the entire implementation of the checksum. Statistically only about 25% of bit errors are detected, however, as stated above, data correctness was not imperative in this application, so 25% is acceptable.

The final byte is a stop byte. It indicates the end of the packet just as the start byte signified the beginning. The stop byte's literal value is 0xFF.

5.8.4 hardware design

The hardware creation consisted of three different boards: a server board, a shake/vibrate board, and a touch/heat board.

Microprocessor

Two different PICs were chosen for the different boards. For the main processors for the personal ambient displays, I chose to use the MicroChip PIC16C63. The 16C63 was chosen because it has ample I/O pins, a good amount of RAM and programmable ROM, and it had a slim reduced width 28-pin PDIP package, which went well with the minimalist size constraints. Initially, all boards were prototyped using the PIC1684, which is a much smaller microprocessor in all respects, but has some nice features like erasable programming for doing rapid application development. This was fine for prototyping the RF protocol and some simple actuator/sensor combinations, however when incorporating the device-specific code for more complex devices, the program ROM blew out on the 16F84. The choice was made to use the C63, which had much more program ROM and RAM. It also has some convenient features like chip-supported pulse width modulation (PWM), which later became a necessity to run motors and heating devices.

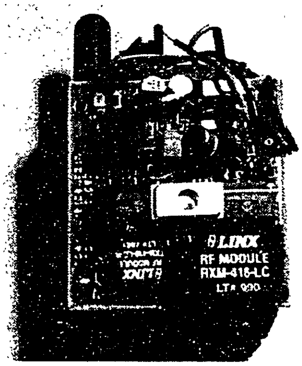


Figure 5.19
A "Shaker" personal ambient display. From bottom to top, the RF chips, microcontroller, and accelerometer are visible

RF Devices

The RF components used are CPCA (Carrier Present Carrier Absent) serial RF modules by Linx Technologies transmitting at 418Mhz. These chips take serial data from the PIC and transmit them over RF using a CPCA protocol. A reduced height whip style antenna is used in the end product to maximize the transmission range, however a simple wire could have been feasible. From some rough testing, it was determined that transmission distances of about 15-25 meters were possible by using the whip-style antenna in cluttered, active environments.

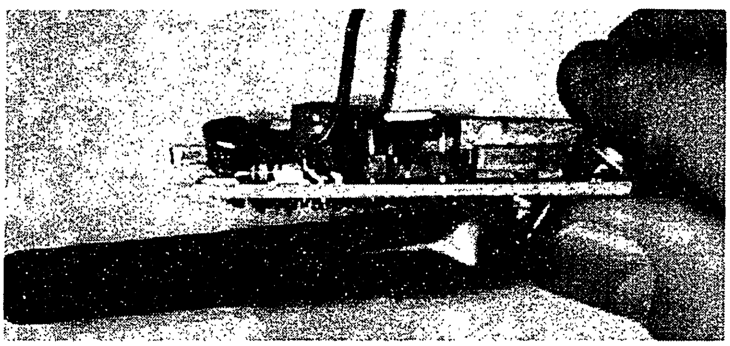


Figure 5.20
The whip antenna visible from a profile view

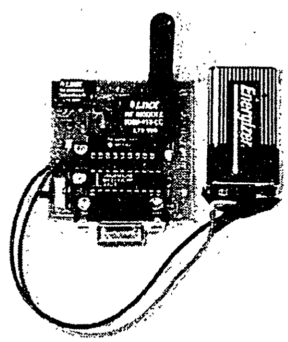


Figure 5.21
A server board that can be connected to a computer as a hub, or be used as a repeater

To increase transmission distance, a repeater was created that could forward packets. The implementation of the repeater was very basic. It simply sits and listens to the RF and retransmits whatever it hears. However, using more than one of these "simple" repeaters could cause infinite message loops. The simplest method for eliminating repeater ring would be to add information, such as a repeat counter, to the packet. Every time a repeater received a packet the repeater would check the repeat counter. If it were above a certain threshold it would do nothing, however, if it were below that threshold it would increment the counter and rebroadcast the packet with the new count. This solution eliminates infinite ringing, but does allow an individual message to ring between repeaters a finite number of times.

Power Supplies and Batteries

The power supplies on all the different boards were based on the 78L05 voltage regulator. The design of this power supply was taken from the power supply of the iRX 2.1 board developed by Rob Poor (Poor, 1999). The 78L05 can cut a voltage source between 7-12V down to a steady +5V. The main problem with this power supply is that the 78L05 throws away all of the voltage above 5V. Using this wasteful power supply hooked up to a 9V battery, the average time per battery that was attained was approximately 4 hours. This is not acceptable for a final product, but it was enough for prototyping.

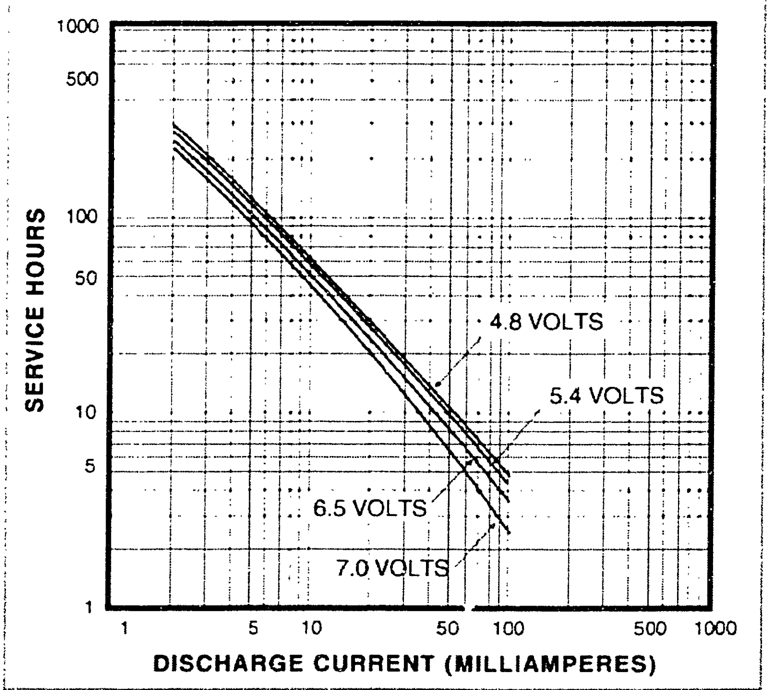


Figure 5.22
In this graph, battery service hours are shown as a function of discharge current for a 9 Volt battery. The personal ambient displays are driven near the 4.8 V level around 120 milliamps. This results in a battery life of about 4 service hours.

One of the contributing factors to the extremely low hours to battery ratio is the fact that many of the actuators used were driven with high amperage pulse width modulation. In fact, two 2N3904 transistors had to be piggybacked to draw enough amps for the peltier junction. To combat this power supply problem, a switching power supply, like the PowerTrends 5101, could be used. This supply can take a slightly larger range of inputs, and outputs a steady +5V. It can support up to 1 Amp of current, which is more than enough to power any of the actuators. Also, it is a switching power supply, so instead of throwing away the voltage above 7V, it utilizes all of the battery's capacity, increasing its life. Although it has not been tested, it is expected that a board with the 5101 power supply, combined with more energy efficient controller code, could have a battery life expectancy on the order of a week or more.

In my "hot/cold" implementation, about 126 milliamps run through the peltier junction when it is being heavily driven. This creates a temperature differential between the hot and cold side on the order of 10°C (16°F). The hot side usually can be ramped up to a maximum temperature of 32.2°C (90°F) as the cold side falls to around 23.3°C (74°F). Skin temperature greatly varies, but is usually in the range of 33°C (91°F), with a sensitivity to notice changes of about 4-8°C. In practice, people could usually feel the temperature change, albeit, mildly. The cold side is more apparent than the warm side, as it is further away from the normal skin temperature. Like stated above a switching power supply like the PowerTrends 5101 that could support enough current would be vital for a next round of implementation.

The peltier junction method of heating was tested against resistive heating. To do this, I ran 122 milliamps at 5V through two 82 Ohm resistors in parallel (an effective resistance of 41 Ohms). I bonded these resistors with thermally conductive silicone paste to a copper plate the same size as the peltier junctions. The resulting heat source was significantly hotter than the peltier junction at the location of the resistors, but did not transfer well throughout the rest of the plate. This perceptually felt very much like a point source. With proper choice of housing material, heat transport would improve. However, when heat delivery is needed over a large area, the peltier junction performs relatively well.

6 discussion

The creation of these various personal ambient displays and the earlier ambient display prototypes has served as an entry-point into identifying and elaborating upon the most important aspects of ambient display design. In this section, I discuss ideas central to these current implementations and topics that have broader implications for ambient display design in general, both personal and room scale.

The biggest issues I encountered in making personal ambient displays and ambient displays dealt with the input and output mappings, dealing with latency, and in design issues such as location on the body and form factors.

6.1 output reflects input

"The power of the unaided mind is highly overrated... The real powers come from devising external aids that enhance cognitive abilities."
-Don Norman, from his book, Things That Make Us Smart

Human communication heavily relies on the powers of abstraction and representation, which Norman defines as the ability to represent perceptions, experiences, and thoughts in some medium other than that in which they have occurred, abstracted away from irrelevant details. To do this successfully, he argues that a designer needs to work on "fitting the representation to the task" and "fitting the artifact to the person."

6.1.1 fitting the representation to the task

Graphs are often preferred over tables of numbers because of their ease of accessibility. This is the essence of ambient display design: taking a data source and representing it in some other form so that it is more suited to a task. The goal of an information display designer is to come up with this mapping such that the data is in its most comprehensible and legible form.

While quantitative information is most readily deliverable by computers, it is not what people always need, or even desire. Instead, there are times when we would like to receive the "gist," or a summary of information in a qualitative manner, rather than receiving exact numbers (Tufte, 1983). Ambient displays are qualitative displays. The difficulty in creating qualitative displays lies in the fact that the information to be displayed is in a quantitative form that must be translated through some sort of mapping to a qualitatively interpreted display.

One method of creating this shift to a qualitative display is demonstrated by the Pinwheels. A varying quantitative value is used as an input to the pinwheels. Perhaps a value from 1 to 1000, though any range is usable. This is then directly mapped to the speed of the

Pinwheels' rotation. The Pinwheels spin extremely slowly when a value of 1 is input and runs at maximum when a value of 1000 is input. The user views the spinning pinwheel and than evaluates how fast it is going. While the pinwheel is spinning at a rate proportional to the input, the value is not exactly known, the user has a more qualitative understanding that the pinwheel is moving slow, or fast. In this way the pinwheels are still actually quantitative gauges of the information source, but due to the interpretation necessary by the user, they become a sort of "fuzzy" gauge.

In the same way, web usage is sometimes viewed by sorting through log files and viewing statistics. However, the best server statistic packages create dynamic graphs and meters that visually show the load on a server. Usually, this is done such that when a server gets busier, more area is filled in on a meter. The information is either zero or more, up to some potentially infinite positive number. If this information was to be translated to the "hot/cold" personal ambient display, only the "hot" effect would be needed, as the data being represented never goes into the negative realm that a cold object would logically indicate. If stock information was being mapped to the "hot/cold" object, ample use of both hot and cold would be needed, as a stock can go up or down, and sometimes just stay the same.

6.1.2 fitting the artifact to the person

Once the representation is fit to the task, the next step is to fit the display artifact to the person. Norman proposes a rule for this step of design that he calls the *Perceptual Principle*:

> *Perceptual and spatial representations are more natural and therefore to be preferred over nonperceptual, nonspatial representations, but only if the mapping between the representation and what it stands for is natural- analogous to the real perceptual and spatial environment.*

The ambient display work clearly follows the current trend of "multi-modal" interfaces that point towards perceptual, spatial representations. The multi-modality these ambient displays posses is a direct result of their physicality; it is a not simulated by a processor. As the display moves, the visual cues, as well as all the other effects it has on the physical environment, enrich the output of the display. For example, as clearly seen in the user studies (presented in Chapter 7), the vibration of the Water Lamp and the spinning of the Pinwheels can be heard. These multimodal outputs could be simulated to accompany a conventional visual display, however it would be difficult for the various outputs to have the quality feel of the real physical device.

This is an aesthetic argument, however I have noticed it in practice. During the design studies in the ambientROOM, many people reported that the sampled, synthesized sounds in the Room became annoying after days of repetition. In particular, people complained that sounds that are looped in some kind of discernable way, or sounds that seem to be coming from an artificial source, tend to become annoying very quickly. But, in that same time period, another project called "The

Interactive Poetic Garden" employed a real stream of water flowing down a bed of rocks in an adjacent space (White, Small, 1998). This created a significantly audible, persistent acoustic noise. In contrast to the sounds of the ambientROOM, people were drawn to, and relaxed by the subtle sounds of the flowing water. In this case, the physicality of the display lent a kind of entropy to the sound, which made it soothing. A professional sound designer might be able to create a pleasing soundscape with great effort, and expensive tools. However, the "Garden" project has shown that a pleasing, controllable, ambient information soundscape is easily possible through physical means.

One of the ways a representation can fit the person is through being consistent with a design metaphor that a person can relate to, and bring previous knowledge to. Ishii has proposed a design metaphor based specifically on the physicality involved with nature. This design metaphor can be seen as influencing many of the designs of ambient displays. The Water Lamp is about shadows thrown by light and water movement, the Pinwheels spin in a "wind of bits," and the "hot/cold" personal ambient displays are designed to transmit the "warmth of touch" over a distance. The idea behind this design metaphor is that humans are keenly adept at awareness of natural phenomena, and that this skill can be leveraged as a means of information display that is both coherent and aesthetically pleasing.

6.2 latency

Once a satisfying mapping has been designed for the task and for the person, issues of signal transmission come into play. After using the personal ambient displays for a period of time, it became apparent that the latency, or the time it takes for the signal from one device to reach another, was critical to the overall effect. This effect is most clearly seen in using the "shaker" objects. If two people are standing next to each other, and one person activates one object, the person on the receiving end expects the signal to be instant. If it is not instant, people usually believed that there was something wrong. A more dangerous problem was that some people lost the sense of causality if the latency was too large. They did not equate their actions as having an effect on the other object.

This led me to believe that for "same room" communication, latency between communicating devices must be perceptually instantaneous. However, an interesting phenomenon occurred in using the hot/cold objects. For them, the latency problem was much less of an issue. I believe that this can be equated to the very character of the display.

Temperature is a slow-onset display. People are naturally accustomed to waiting for something to heat up, and waiting even longer for things to cool down. It is a characteristic of the medium. Vibration, on the other hand, is a fast-onset display. When something is shaken or moved, it is instantly perceptible.

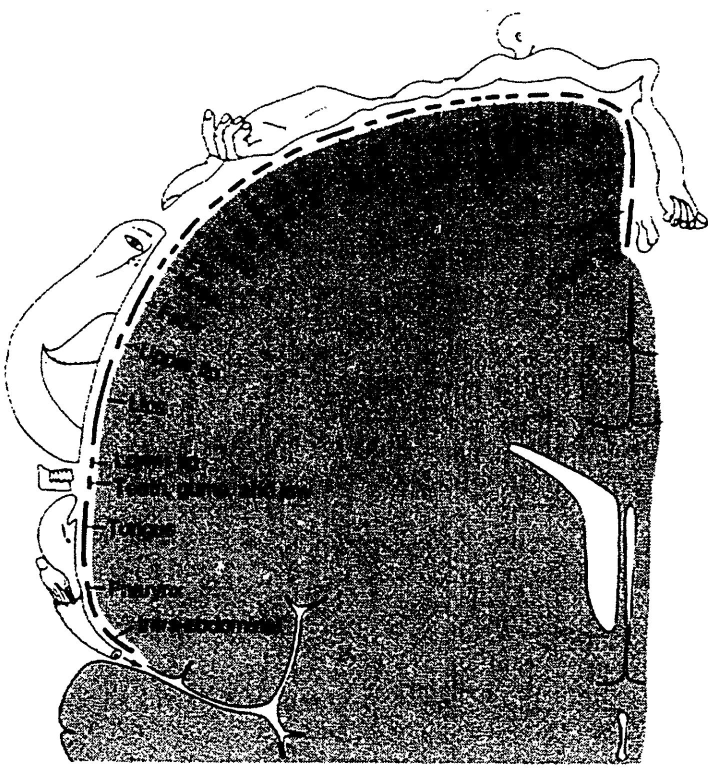
These expectations, based on people's knowledge of the medium, are carried over into the perception of a display. For a slow-onset display, like heat, latency is less important. For a fast-onset display, like vibration, latency is very important. This again speaks to the issue of choosing a modality that corresponds well with the type of information being sent. This finding is very much tied to our perceptual system and how it functions with regard to the sense of touch. This led me to look back into the literature about the tactile perceptual system.

6.3 touch

Central to this work is the aspect of touch. By reviewing the basic knowledge we have about how touch works and is perceived in the human body, a number of design requirements and guidelines can be made.

6.3.1 regions of the body

Certain areas of the body are far more sensitive to touch stimulus than others. This chart maps out the sensitivity of various regions.



Sensory homunculus

Figure 6.1
Sensitivity to touch varies between different regions of the body. This diagram gives a graphical representation of which areas are more sensitive than others

**Figures 6.1, 6.2, and 6.3 are taken from the book* <u>*Sensation and Perception*</u> *by Coren, Ward, and Enns*

By glancing at this chart, it is obvious that the hands, feet, and face are the most sensitive areas of the body to a prodding touch. This is useful knowledge. However, if a display has a time-course of longer than a few minutes, serious consideration must be given to how that area of the body adapts.

6.3.2 adaptation

Touch sensations adapt. This is a simple phenomenon we deal with everyday. For instance, often shoes, a belt, or a shirt might feel uncomfortable, but over time the sensation goes away. Similarly, a person will adapt to the signals from a personal ambient display.

There are a few simple findings in the literature regarding touch adaptation that are worth noting. The first is that the heavier the stimulus, the longer it takes for it to attenuate. Also, the larger the area covered by the stimulus, the quicker it disappears. The time period of adaptation has also been widely considered. It has been found that adaptation is very rapid for the first few seconds, and that after about 3 seconds, the stimulus' intensity is about one-quarter of its original self. These findings were made by pressing a small rod against a person's finger. When dealing with a vibrating stimulus, a stimulus of a different tactile character, or on a different location on a person's body, the adaptation values usually increase. For instance, for a vibrating stimulus on a forearm, adaptation is not complete for over a minute at times.

6.3.3 hot and cold

One of the aspects of this project that is the most novel and unexplored is in the use of temperature as a display mechanism. Traditionally, heat has not been used as a display medium for a variety of reasons. For one, it is not an information-rich medium. An object, surface, or room can only get hot or cold. There is only one degree of freedom. Also, it is a slow-changing medium that consumes much power. Perhaps most importantly, using hot and cold things can be dangerous. In the most extreme cases, burns and fire could result. The worst case scenario in using heat is a bit worse than with using an LCD (although, if not properly used, LCD's can have some nasty side effects as well). However, I believe that some of these impedances can be overcome, and that we might find some good applications for a temperature display.

Perceptually, temperature is much like any other sense, in that it has thresholds, adaptation periods, and intensity limits. Skin works to maintain a constant internal body temperature of 37 °C (98.6 °F). To do this, the body tries to maintain a skin temperature of about 33 °C (91 °F). This is called *physiological zero*. Deviations from this skin temperature are what causes feelings of warmth and cold.

There is a range of temperatures close to physiological zero that are not perceptible as being warm or cold. Like other tactile stimuli, this range changes with adaptation. Kenshalo and Scott (1966) performed a study that found that the zone around perceptual zero that was undetectable by the skin was on the order of 4 to 8 °C, depending on adaptation. This chart shows their findings over time:

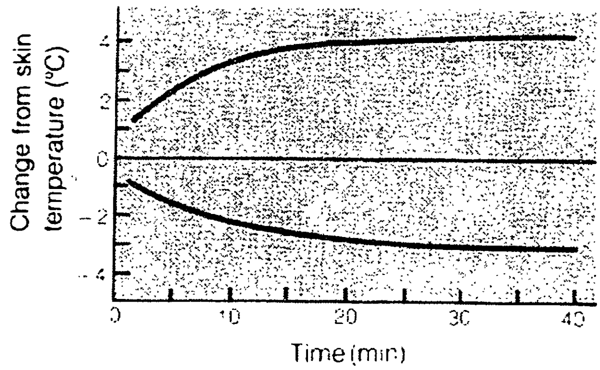


Figure 6.2
This chart shows, over time, the temperature change (from physiological zero) that usually goes undetected

This is significant for a personal ambient display designer, as it indicates the kind of temperature jump away from physiological zero that is needed to be perceptually significant.

Another phenomenon useful to know about is that sensitivity to lowering the temperature is greater when skin temperature is colder, and sensitivity to raising the temperature is greater when skin temperature is warmer.

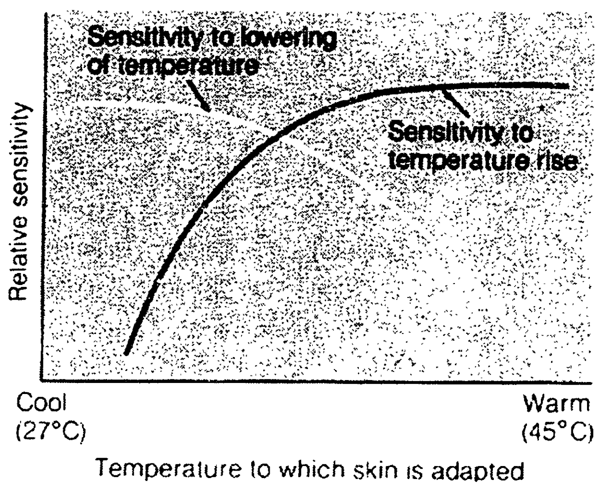


Figure 6.3
Sensitivity to changes in temperature is different depending on whether skin temperature is warm or cool

Also, like with all touch sensations in general, different areas of the body are more sensitive to warmth and cold changes than others. For warm stimuli, the head is the most sensitive, while the arms and legs are the least. The torso of the body is intermediately sensitive. On the other hand, the torso is the most sensitive to cold temperatures, with the limbs intermediate and the head the least.

One approach to overcoming the adaptation problem could be to use a "comparison of temperature" method, instead of just an all-heat-up or all-cool-down method. One part of the device could be kept at a constant "reference" temperature, while another part would vary.

Noticing changes from a reference is a lot less subject to adaptation effects. This "reference" method would only work with form factors that change location on the skin at different times.

This brings up an important point. Working with warmth and cold creates new, untraditional challenges with form factors and packaging. The first challenge is that the packaging must be thermally sufficient, or "melt-free". Beyond that, a packaging material is desired that provides efficient, fast thermal delivery from source to surface.

6.4 form factors

The concentration of this thesis was to create the basic technology to accomplish the desired display and communication capabilities, and to make it as small as possible. When those goals are achieved, an entire world of opportunity arises in designing unique and innovative form factors to support personal ambience. For instance, an array of the tiny "hot/cold" objects could be built into a chair. Or, a linear actuator could replace the pager motor to create an object that could change shape.

In my implementations, I aimed at creating two kinds of form factors:

- a pocket carried object, like a keychain
- a watch

These two form factors satisfy my goal of making personal devices, as they are commonplace items most people use. My original conception was to only think of these devices as something that is carried, like a keychain. However, upon reflection, it was realized that many women do not have pockets in their clothes, and keep personal items in a purse. In that case, objects with tactile sensations would not work, as they have no connection to the body. That led me to think about the devices as being worn, and the watch is the primary embodiment of a "worn" display.

The scope of this thesis did not include a foray into the realization of these various form factors. However, I believe that designing form factors is one of the primary areas of future work in the ambience field. Even more so than with graphical user interfaces, the "look and feel" of a tangible user interface is critical to its success or failure.

7 pilot user studies

In an attempt to better identify the design issues I am grappling with, and to shed some light on the usage of the displays that have been created, I have given thought to a more rigid process a designer of ambient displays should undergo when creating a new display. I have identified a set of experiments that can point to some issues a designer must ask of a new display. These experiments congeal into a process that should be carried out on a display after it is created, but before it is deployed.

When a person looks to display information on an ambient display, it is imperative that they understand how people perceive that display. For instance, the Water Lamp's motor is capable of being driven at six different speeds. This might lead a person to map six different levels of information to the Lamp. However, it has been found that a person cannot perceive differences between all of these six levels. Instead, people seem to only be able to identify four different levels of activity in the Lamp. An understanding of aspects like these is crucial for an information designer who wants to deploy an ambient display.

With issues like this in mind, I conducted a number of pilot user studies with the Water Lamp and Pinwheels. For all of the experiments detailed here, six undergraduate male subjects were tested in multiple trials of each test. The experiments with the Water Lamp were conducted in a classroom that was relatively empty, and free of distraction beyond the device being tested. The experiments with the Pinwheels were performed in a group's research space during a time of minimal usage and traffic.

These experiments are not intended to be entirely controlled or definitive. These are merely a set of pilot studies conducted to better identify the design issues that are faced, and gain initial insight into what the serious problems might be in the creation of ambient displays.

7.1 resolution of the water lamp

The goal of the first study was to find out how many "different states" can be perceptually attained with the Water Lamp when it is in the foreground of a user's attention, and when it is in the background of attention.

Foreground:

The Water Lamp's motor can drive the Lamp at six different levels of intensity. First, I ventured to find out how many different levels of intensity a user could perceive.

Subjects were asked to actively perceive (watch and listen to) the Lamp, and indicate whenever they noticed any change in its state. In some trials, the intensity of the ripples started slow and increased, and in other trials, the Lamp was maximally driven and slowed over time.

The results were very consistent, with very minimal variance between subjects. Each of the 6 subjects ran 4 trials each, for a total of 24 trials. On average, the subjects perceived about 4 different states in the Water Lamp (Mean = 4 states, Standard Deviation = 0.577).

This result is interesting, as it indicates that even though more than 4 levels of control exist over the Water Lamp, a user can usually only perceive 4 different states, even while paying it full and total attention. Subjects perceived 5 states in only a few trials and not once was 6 states ever perceived.

Background:

Next, the same kind of experiment was conducted, except that the subjects were instructed to concentrate on playing a computer game as a "foreground" task. They were asked to play the computer game to the best of their ability, and if they should happen to notice a change in the intensity of the Water Lamp, to indicate so. The foreground task that was chosen was playing Pac-Man®. This task was chosen because it requires significant, constant focused attention to play successfully. Subjects sat at a desk, and played the game on a laptop computer. The Water Lamp was positioned directly in front of them, 10 feet away.

The results were again, very consistent with very minimal variance between subjects. Each of the 6 subjects ran 4 trials each, for a total of 24 trials. On average, the subjects perceived about 2 or 3 different states in the Water Lamp (Mean = 2.58 states, Standard Deviation = 0.64).

This result was a bit surprising, as I had anticipated a much larger drop-off in the ability to perceive the display. When questioned about the method they used to determine changes, every single subject said that their best indication of the state of the display was the sound that it was creating. The foreground task was very visually intensive, but they found that they could distinguish the activity of the Water Lamp through the subtle, barely perceptible sound of its motor. This indicates that, as it was used here, this is an auditory display.

This surprising result points to a number of issues, one being the selection of the foreground task for this experiment. Pac-Man is a very visually intensive foreground task. I imagine that if the foreground task had been something sound-intensive, or linguistically intensive, the results might be very different. Later, an attempt was made to test this dependence on sound.

7.2 resolution of the pinwheels

Next, a similar study was performed with the Pinwheels. The goal was to find out how many "different states" can be perceptually attained with the Pinwheels when used as a foreground device, and as a background device. The same procedure was used as in Experiment 1.

with the Water Lamp, except that the location was changed (this study was held in an open research space instead of a classroom). Again, 6 subjects were run through 4 trials each, for a total of 24 trials.

There are a few differences between the Water Lamp and Pinwheel displays that are significant. Instead of just being one object, the Pinwheels are a collection of 5 objects. For the sake of this experiment, all 5 Pinwheels were made to speed up and slow down in unison; they were treated as a collective whole, instead of separately controllable entities. However, like the Water Lamp, they are controllable in a certain number of steps of increasing intensity (in this case, increasing the speed of rotation). The Pinwheels are controllable to 10 discrete steps; one being slowly moving, and ten being the motor running at top speed.

Without question, subjects clearly perceived all 10 different states in the Pinwheels, when in the foreground as well as in the background.

Again, subjects pointed to the varying sound levels between each motor level as the best indication of state. In this case, the sound levels were so distinct that subjects had no problem perceiving changes in state.

7.3 transitions with the water lamp

Experiments 1 and 2 tried to simply get an indication of how many perceivable states there are in the foreground and background use of the Water Lamp. It does not speak to the issue of time or order. Experiment 3 tries to address these factors. For instance, I wanted to find out whether or not a person will notice a change in the display if it rises from a low intensity to a high intensity quickly, and also, whether or not a person notices a change if it gradually decreases its activity instead.

To do this, 6 subjects were run through 2 trials each of a randomly selected pattern of intensities and transition times, for a total of 12 trials. Again, they were asked to attend to the computer game foreground task, and indicate if they ever noticed a change in the state of the ambient display. I was able to receive information from a computer documenting the intensity of the Lamp at all times, and have analyzed what kinds of patterns led subjects to notice a change.

Twelve times (once in each trial) there was a transition between a soft intensity of 1 and a hard intensity of 6. All twelve times, subjects indicated that they noticed the change. Also, twelve times, there was a quick transition between a hard intensity of 6 down to a small intensity of 1. Again, each of these twelve times, subjects indicated that they noticed the change.

On the other hand, there were 12 times when an intensity would change by an increment of only one level (say, from 1 to 2, or 5 to 4). Changes were noticed by subjects only 2 of these 12 times.

Those two cases were the only clear cut results. In cases where there was a transition that jumped 2 or 3 intensity levels (such as from 1 to 3, or 5 to 2), subjects would not notice more often than not. Only about a quarter of the time would subjects report that a change had occurred. However, in cases where the intensity would jump by 4 levels (from 2 to 6, or 5 to 1, for instance), subjects indicated that they noticed often, but not all (roughly 75%) of the time.

By simply glancing at the data, it is obvious that the subjects consistently noticed the biggest changes of intensity, and did not notice the smaller changes. As expected, gradual changes in intensity would sometimes warrant attention, and sometimes go unnoticed.

7.4 location of the display

Next, I wanted to investigate what effect the location of a display had on its perception. To do this, Experiment 3 was repeated with the Water Lamp moved 90° degrees off-center. Again, 6 subjects were each given 2 trials each, for a total of 12 trials.

The data received from this experiment was remarkably similar to the data received in Experiment 3. Moving the display off-center does not appear to produce any significant differences in a subject's perception of the display.

Again, when questioned, each subject indicated that they were using the sound created by the display, more than anything else to monitor changes in its state.

7.5 removing the sound

After running these experiments, I realized what a huge impact the sound of a display has on its perception. People had been using sound as the primary tool of attending to and analyzing the display. To prove this, and also test the display for its visual effectiveness, I took the element of sound away from the subjects.

I performed Experiment 3 on the Water Lamp again; where subjects are asked to indicate when they notice a change in the display while completing a foreground task. This time, subjects wore earphones that played the sounds of the Pac-Man® game in their ears. This eliminated any audio cues they might have received from the ambient display. Again, 6 subjects performed 2 trials each.

As expected, without the aid of auditory cues, subjects performed far worse in noticing changes in the display. The only change that tended to be noticed was when the display would go from an intensity of 1 to an intensity of 6, or vice versa. Only these very major changes in state were noticed. Almost without exception, all other transitions were missed.

7.6 lessons

The biggest lesson learned through the pilot user studies was that people tended to use the auditory aspect of the ambient displays more so than the visual aspect. Even when observing the displays in the foreground of their attention, most subjects reported that the sound was the best indicator of the display's state.

When performing a visually intensive foreground task, it makes sense that a person would not be able to notice visual change in the periphery of their sight. The area an eye can focus on (its foveal view) is actually quite narrow, only a few degrees. However, it was surprising to notice people's reliance on sound even with their vision free. One possible explanation of this is that humans are very adept at perceiving changes in pitch. In both of these cases, the change in pitch might have delivered more information than the dedicated visual channel.

I also learned that the Water Lamp has a maximum of 4 (or possibly 5) perceptual levels of intensity to work with, while the Pinwheels have many more. Also, it has been shown that when a person is performing an intensive foreground task that engages both the visual and auditory systems, the ability to perceive changes in an ambient display decreases, but is possible (that is, if the ambient display uses the modalities of vision and hearing). Further, evidence has been received that a display can come into the foreground of a person's attention by rapidly, drastically changing the intensity of the display.

These are simple, yet integral results to the very basic character of an ambient display. By running this set of studies on a display, a baseline can be set that indicates how people perceive the object, which can then be used by an information designer in the mapping of an information source to the display's output.

8 conclusion

8.1 summary

In this thesis, I have introduced the concept of a personal ambient display. I have also positioned this new work in the context of previous work done in this field. I designed and implemented a variety of prototypes of both ambient displays and personal ambient displays and received various kinds of feedback and information from their preliminary usage. The primary areas of importance and challenge in technical implementation and theoretical positioning have been identified and addressed.

I have determined specific details about the perception of two devices that can be used by information designers who want to deploy these as ambient displays. In addition, this work has identified what I believe to be the critical areas of design that need to be addressed when creating a new instance.

Of particular interest is the infrastructure that has been created during the realization of personal ambient displays. By making the devices small, wireless, and individually addressable, they can be easily embedded in different form factors and different locations to serve new purposes. For instance, a few dozen of the "hot/cold" personal ambient displays could be embedded in a chair, creating a very different kind of temperature display.

8.2 future directions

Future directions in this field are abundant. The obvious next step would be to create a series of ambient displays tailored for a specific task that could be used, tested, and iterated upon over a long period of time. Realistically speaking, all of the implementations introduced in this thesis only reached the prototype stage where they could be used for hours, not days at a time. To accomplish this is a logical and requisite next step in any future work, as I expect it would bring about altogether new issues of ambient display design.

In creating these prototypes and implementations, I have taken a decidedly exploratory approach. An alternative approach would be to try to design and implement an ambient display for a very well defined and specified task. At this point in the research, I believe that approach would pay the most dividends.

Related specifically to personal ambient displays is the need for future work in simple, tactile messaging. Researchers in the CSCW field and even much of the general public who use the internet have become enamored with the various techniques for keeping an awareness of friends, colleagues, and important information. Increasingly, this information is being moved towards small, personal devices. I am convinced that these tools should not be relegated to only displaying information through screens and sound, and not only accept input from buttons, voice, and pens. To be truly powerful, these devices should take advantage of their sense of motion, position, and contextual state and be able to display information in ways that best fit the person and the task.

By enabling the physical world around us with display capabilities and extending similar functionality to personal devices, people can get easier, more comfortable access to information. There are many technological and design issues left to be resolved, however, I believe that the work presented in this thesis provides a solid start down that road.

appendix a: sample code

This section includes some sample code from Hive and the PocketServer connection/reconfiguration schemes.

Hive Shadow Code for Pinwheels

This first sample code chunk is the "shadow" for the Pinwheels in Hive. In essence, the shadow is a bit like a device driver. (The Pinwheels shadow written as a style guide by Hive developer Matthew Gray).

```
package edu.mit.media.hive.shadows;
import edu.mit.media.hive.support.Debug;
import edu.mit.media.hive.agent.BaseAgent;
import edu.mit.media.hive.sysinfo.*;
import edu.mit.media.hive.beans.*;
import java.io.*;
import java.util.*;

public class Pinwheels
  implements Shadow
{
  // The output stream for the pinwheels
  PrintWriter out;

  // The current state of the pinwheels
  int pinwheelSpeeds[] = new int[5];

  // This function is currently unused, but should indicate
  // whether the device is actually connected
  public boolean isDeviceThere() {
    return true;
  }

  // This is called when the shadow is created
  // A pair of streams is handed to it which it communicates
  // to the device over
  public void init(InputStream is, OutputStream os){
    out = new PrintWriter(os);
    Debug.println(Debug.NOTICE, "Outputstream set");
  }

  // This is the public function to spin one of the pinwheels at
  // a particular speed
  public void spin(int which, int howFast){
    // Only 5 pinwheels
    if(which > 4)
      return;
    // Don't overstress them
    if(howFast > 12)
      howFast = 12;
    pinwheelSpeeds[which] = howFast;

    // If we're connected, actually adjust the speeds
    if(out != null)
```

```
        spinEm();
    else
        Debug.println(Debug.NOTICE, "Waiting for my channel...");
}

// Send the commands to the pinwheel to set them to the appropriate
// speeds
private void spinEm(){
    System.out.print("Sending to pinwheels: ");
    out.print("L");
    System.out.print("L");
    for(int i=0;i<5;i++){
        out.print(" 0");
        System.out.print(" 0");
        out.print(Integer.toHexString((int) pinwheelSpeeds[i]));
        System.out.print(Integer.toHexString((int) pinwheelSpeeds[i]));
    }
    out.println();
    out.flush();
    System.out.println();
    for(int i=0;i<5;i++){
        System.out.println("Pinweel "+i+" set to "+pinwheelSpeeds[i]);
    }
}

// This shadow does not have a default agent
// The return from this function may be ignored anyway
public BaseAgent getDefaultAgent() {
    return null;
}

// Have the shadow tell us how it expects to talk to the device
public LocalChannelConfig getPreferredLocalChannelConfig(){
    // If we wanted to talk directly over serial line 1
    // to the pinwheels, at 19200, we would do this:
    //     return new SerialChannelConfig(1, 19200);

    // But, in reality, SGI serial ports are picky, and we want to
    // talk to a simple tcl script, so we do this:
    return new ProcessChannelConfig("/usr/local/bin/wish8.0 /mas/u/mkgray/pinwheels/pinwheels.tcl");
}
```

PocketServer Device Code

This code is from the connection/reconfiguration mechanism created independent of the Hive system, called PocketServer.

```
import java.awt.*;
import java.util.*;
import Packet;

public class Device
{
        public int      id;
        public Point    loc;
        public Vector   links;

        //*********************************************************************************
        // CONSTRUCTORS
        //*********************************************************************************
        /** Creates a new device at loc (-1,-1) */
        public Device() {
```

```
		loc = new Point(-1,-1);
		id = -1;
		links = new Vector();
		clearLinks();
	}

	//*************************************************************************
	/** Creates a new device at loc (p.x,p.y) with id = n*/
	public Device(int n, Point p) {
		id = n;
		loc = new Point(p.x,p.y);
		links = new Vector();
		clearLinks();
	}

	//*************************************************************************
	// METHODS
	//*************************************************************************
	/** Checks whether there exists a connection to another device */
	public int isConnected(Device dev) {
		// Walk through the vector and check each device
		for(int i=0;i<links.size();i++) {
			if(((Device)links.elementAt(i)).id == dev.id)
				return i;
		}

		return -1;		// didn't see the element in the links vector
	}

	//*************************************************************************
	/** Adds a connection to another device */
	public void addLink(Device dev) {
		//if it's not already in the list, add it
		if(isConnected(dev) == -1) {
			links.add(dev);

			// Transmit the add connection packet
			Packet.transmit(Packet.ADD, dev.id, id);
			System.out.println("cmd: " + Packet.ADD + "; dev_id: " + dev.id + "; data: " + id);
		}
	}

	//*************************************************************************
	/** Deletes a connection to another device */
	public void deleteLink(Device dev) {
		// Locals
		int index;

		//if it's not already in the list, don't worry about it
		index = isConnected(dev);
		if(index != -1) {
			links.removeElementAt(index);

			// Transmit the add connection packet
			Packet.transmit(Packet.DELETE, dev.id, id);
			System.out.println("cmd: " + Packet.DELETE + "; dev_id: " + dev.id + "; data: " + id);
		}
	}

	//*************************************************************************
	/** Clears the link table */
	public void clearLinks() {
		links.clear();
	}
}
```

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