Subtle, Intimate Interfaces for Mobile Human Computer Interaction

by

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Abstract

The mobile phone is always carried with the user and is always active: it is a very personal device. It fosters and satisfies a *need* to be constantly connected to one's significant other, friends or business partners. At the same time, mobile devices are often used in public, where one is surrounded by others not involved in the interaction. This *private interaction in public* is often a cause of unnecessary disruption and distraction, both for the bystanders and even for the user. Nevertheless, mobile devices do fulfill an important function, informing of important events and urgent communications, so turning them off is often not practical nor possible. This thesis introduces *Intimate Interfaces*: discreet interfaces that allow subtle private interaction with mobile devices in order to minimize disruption in public and gain social acceptance. Intimate Interfaces are inconspicuous to those around the users, while still allowing them to communicate. The concept is demonstrated through the design, implementation and evaluation of two novel devices :

- **Intimate Communication Armband** — a wearable device, embedded in an armband, that detects motionless gestures through electromyographic (EMG) sensing for subtle input and provides tactile output;
- **Notifying Glasses** — a wearable notification display embedded in eyeglasses; it delivers subtle cues to the peripheral field of view of the wearer, while being invisible to others. The cues can convey a few bits of information and can be designed to meet specific levels of visibility and disruption.

Experimental results show that both interfaces can be reliably used for subtle input and output. Therefore, Intimate Interfaces can be profitably used to improve mobile human-computer interaction.

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Intimate Interfaces

Chapter 1

Introduction

The functionality, connectivity and computational power offered by contemporary mobile and wearable devices is advancing rapidly, however, their interfaces continue to mimic those of desktop computers. Yet the conditions of use at the desk are very different from when in a mobile context. Consequently, mobile interfaces recently received much attention from the Human-Computer Interaction (HCI) community [73, 69, 53, 3]. Important issues of the use of technology in a mobile context include: the amount of attention a user can devote to the interface, the type of input that can be performed on the move, the limited size of graphical displays, and the social acceptance of devices and interaction techniques. The use of mobile devices often happens in public places (e.g. offices, libraries, museums, theaters, restaurants) or on public transportation (such as buses and trains), where the user is surrounded by others not involved in the interaction. Using a mobile device in a social context should not cause embarrassment and disruption to the people in the immediate environment. The problem is made evident from the number of signs that can be found in public places inviting or ordering people to turn cell phones off (Figure 1-1). Deactivating these devices is an extreme solution, as it completely annihilates the devices's functions and advantages, and indeed users are not inclined to do so. The replacement of ring-tones with vibrating alerts in mobile phones constitutes an example of a widespread subtle interface to improve social acceptance, while still allowing access to the device functionality.

Unfortunately, this idea of subtlety and social acceptance has not yet been generalized and is lacking in other parts of the interface design.

This thesis proposes *Intimate Interfaces* as a new class of interfaces that enable interaction with mobile devices in a *subtle, discreet and unobtrusive manner.* Intimate Interfaces are designed to enable *very personal and private interaction* with mobile devices, require minimal attention and, cause the least distraction and disruption, both to users and to those around them.

Figure 1-1: Signs ordering people to turn off mobile phones as not to disturb others; commonly found in theaters, cafes, churches, trains and other public places.

1.1 Motivation: Sociology and Critical Design Perspectives

The mobile phone, like no other technological device besides, perhaps, the wristwatch, is always carried with the user and is always active. It fosters a *desire*, if not even a *need*, to be constantly connected and constantly in touch with one's significant other, friends or business partners. In western countries each individual has at least one mobile phone, consequently, the device is seen as very personal as it gives the ability to directly reach the individuals rather than their houses or offices. Research in sociology thoroughly examined how mobile phones are used and how they influence the customs and communication style of their users [27, 70, 65, 49].

The degree of intimacy associated to mobile communication is well captured in a paper by Prøitz [70], who describes the daily communication routine in a couple of Norwegian teenagers. The couple communicates in a way that they perceive as intimate, even though at the beginning the electronic communication seemed to produce an intimacy that was disconnected from the real world (and perhaps did not exist in it). When the initial difficulties were overcome, the couple kept exchanging up to 20-25 text messages per day. Many of the messages were short and seemed to have phatic function, they were self-reports of daily activity, such as: "I just woke up now", "I'm finished taking the shower", "I'm finished with eating now".

Still on the theme of mobile phones and intimacy, Fortunati [27] points out that

> "the mobile phone is a device that enables people, when they perceive the surrounding environment as extraneous to them, to contact somebody of their intimate circle, that is, to activate the reassuring procedure of recognition. In other words, people react to the lack of informative immediacy of the place, strengthening communicative immediacy with their social networks by means of the mobile."

Fortunati suggests that in this way the mobile phone has positive effects on the individual's personality:

> "It is a personality that is able to govern space in a new way, overcoming inertia and conversing with time, appropriating itself of its fastest extensions. Secondly, it is a personality that has the power to construct a communicative network to its own measure, and to handle it independently of where it happens

> to be. So, it is a personality that manages to calm anxiety better than previously, as now it is able re-establish contact with the world of security."

These benefits are especially relevant in a context of mobility and travel. However, the benefits are gained at the considerable expense of an uncontrolled "privatization of public space". The privatization refers to the appropriation of space that the individual performs when talking on the phone in public, forcing one's own private conversation on others who are physically around him, but not related to the remote communication. The beneficial effects of mobile communication though, according to Fortunati, are due to phatic communication, rather than real information exchange:

> "It can never be stressed enough how the phatic function of communication (that is, pure contact), perhaps even more than information, manages to produce this miracle. It is the possibility of contacting its own communicative network at any moment that has the powerful effect of reducing the uncertainty that mobility brings with it."

This remark suggests that enabling the individual to be in contact with his or her social network, preserving the phatic communication provided by mobile phones, in a way that does not require nor involve an "uncontrolled appropriation of public space" could be a way to maintain the beneficial effects of mobile communication and to limit its disadvantages. **Intimate Interfaces are designed to serve this purpose, by being inconspicuous to those around the users, while still allowing them to communicate.**

According to this analysis, mobile communication can often be reduced to a matter of being constantly aware of a connection with one's own social circle: "remote awareness". Often, remote awareness has been explored in the context of Computer Supported Collaborative Work (CSCW) and Ubicomp research, generally through desktop applications, tangible artifacts [8] or ambient interfaces [17]. Not as much research has explicitly addressed remote awareness through mobile devices. In a paper about "Provocative Awareness" [29], Gaver reviews a number of critical design projects related to communication and remote awareness between distant lovers, addressing how they differ from systems providing remote awareness for CSCW. Vetere et al. [82] explored the same area through cultural probes, contextual interviews and focus groups. Based on the results of the investigation and on participatory design workshops, design sketches and prototypes were produced. Most of them involve private communication and exchange of small amounts of information. In the same paper it was noted that this type of use is often the result of user appropriation of technology, rather than the result of conscious design of remote communication devices. Examples of such appropriation process are the unexpected success of text messages (SMS) on GSM networks, or the Italian "*squillo*" phenomenon ("squillo" is Italian for "*ringing*"): letting someone else's mobile phone ring for just a few seconds, but cancelling before the phone is picked-up at the other end, so that no call is initiated (and therefore no billing), this reveals enough to the receiver to identify the author of the *squillo*, which can then be interpreted in a variety of ways from "I am thinking of you" to "I am on my way"[26].

The use, or arguably *abuse*, of the mobile phone ringtone, though, can be an additional source of disruption for those around the user, reinforcing the "uncontrolled appropriation of public space" mentioned by Fortunati. On the contrary, remote awareness should be inconspicuous. Disruption and frustration caused by surrounding people interacting with mobile devices have been the focus of other critical designers in recent years. The design firm Ideo together with the artist and designer Crispin Jones designed five "Social Mobiles" [40]. The project explores five radical new ways to interact with mobile phones that enforce respect for other people, as explained in one of the project annotations: "We are interested in the frustration and anger caused by other people's mobile phones". The interfaces presented by Ideo and Jones enforce respect of the others in a variety of ways: one of the designs gives an electric shock to the listener if the speakers talks too loud; another one allows to create audio interferences in the mobile phone conversation of someone who uses their phone inappropriately; yet another prototype allows to communicate quietly by manipulating knobs and buttons rather than talking. Agnelli and Drori [2] propose "a series of three jackets intended to provoke thought and discussion about the idea of presence". The jackets are in fact wearable interfaces for mobile phones and constrain phone conversations in a way that makes the talker more aware of his physical surrounding.

The concept of *"remote awareness"* by definition requires low attention, as one can be aware of someone else's presence in a peripheral way, while engaging in activities other than watching the other person. Involvement in multiple activities at the same time has been observed in human behavior well before the diffusion of mobile technology. In 1963 Goffman [32] wrote:

> "Men and animals have the capacity to divide their attention into *main* and *side* involvements. A main involvement is one that absorbs the major part of an individuals attention and interest, visibly forming the principal current determinant of his actions. A side involvement is an activity that an individual can carry on in an abstracted fashion without threatening or confusing simultaneous maintenance of a main involvement. Whether momentary or continuous, simple or complicated, these side activities appear tot constitute a kind of fuguelike dissociation of minor muscular activity from the main line of an individual's action."

In the same book Goffman also covers the distinction between *dominant* and *subordinate* involvements:

> "A dominating involvement is one whose claims upon an individual the social occasion obliges him to be ready to recognize; a subordinate involvement is one he is allowed to sustain only to a degree, and during the time, that his attention is patently not required by the involvement that dominates him. Subordinate involvements are sustained in a muted, modulate, and intermittent fashion, expressing in their style a continuous regard and deference for the official, dominating activity ad hand. Thus, while waiting to see an official, an individual may converse with a friend, read a magazine, or doodle with a pencil, sustaining these engrossing claims on attention only until his turn is called, when he is obliged to put aside his time -passing activity even though it is unfinished.
>
> Typically, it is expected that a main involvement will be a dominating one and a side involvement a subordinate one, as when a worker smokes a cigarette

> unthinkingly but only when and where the job allows. This relationship, however, is by no means invariable. Many dominating involvements, such as work tasks, can be sustained automatically and unthinkingly for long periods, allowing the individual to devote his main focus of attention to pursuits such as idle gossip, which, however, involving, will be put aside when the task requires attention. A telegrapher , for example, can tap out messages while sustaining a conversational byplay with a fellow worker."

Attending to mobile devices, especially for the remote awareness or social connection applications described earlier, should be treated as a side and subordinate involvement. Intimate interfaces are designed to support this modality and allow mobile device users to attend to them in an intermittent fashion, leaving users able to easily switch back to the dominant activity.

1.2 Background and Related Work in Mobile HCI

Thanks to circuit miniaturization and low power consumption that allows the use of smaller and smaller batteries, mobile devices are increasingly *wearable* and hidden in fashion accessories. Recent technological developments in eyeglass displays [78, 59, 44] make them interesting candidates for the next generation of mobile devices. The display technology is integrated in standard eyeglass frames and lenses and it is barely noticeable to observers. Unlike head mounted displays, eyeglass displays are unobtrusive and do not occupy the wearer's entire field of view, preserving awareness of the environment [30]. Eyeglass displays create a virtual semitransparent screen in front of the user, with resolution between 320x240 and 640x480 pixels allowing the display of about 20 lines of text. This virtual screen is "physically decoupled" from the mobile device it is connected to (e.g. the PDA). This characteristic allows the big advantage of the screen size not to be constrained by the device dimensions (i.e. big display and very small device, PDA or phone). Similarly, wearable audio displays, such as Bluetooth headsets and earphones are often worn continuously and do not influence the size of the mobile device that can be kept in the user's pocket or bag.

However, the decoupling of the device and display can make the interaction design problematic. Recent trends in UI design tend to associate the manipulation and display of information. Examples include touch-screen displays, soft keys (keys placed next to a display, whose function can vary over time because it is indicated on the display), tilt-based interfaces to navigate content in handheld devices [34, 38, 63, 69, 72], and tangible interfaces where interaction with digital content is performed through manipulation of physical icons virtually linked to it [25]. Therefore, eyeglass displays, as well as other disembodied interfaces, require a new interaction paradigm that does not strongly rely on physically manipulating the mobile device. An alternative to display-centric interfaces is an interface centred on the user's body. Gestural interaction has been proposed as an interaction technique for mobile devices [3], and it appears to be a suitable way of interaction with systems based on eyeglass displays. The user performs gestures to issue commands, and the results are displayed on a virtual screen.

Visible gestures, though, can negatively affect the social acceptance of the interface. Lumsden and Brewster [53] question the social acceptance of speech-based and gesture-based interaction. Speech recognition has been criticized as an interaction technique for mobile devices because verbal communication is the most common form of interpersonal communication, so in many situations it would be awkward and inappropriate to start talking to a computer. Hand and body gestures are also an important part of human to human communication. Therefore, the same criticism of speech applies to interfaces based on evident gestures. Gestures for mobile interfaces should then be as inconspicuous as possible.

Few researchers in mobile HCI addressed concerns related to the social acceptance of devices and interactions. Rekimoto [73] refers to *social acceptance*, *unobtrusiveness* and support for *hands free* operation as important features for wearable devices, but he limits the considerations to the aspect of devices, rather than the actual interaction. Lumsden & Brewster [53] refer to social acceptance as one of the concerns that mobile interface designers should take into account, and they question what kind of gestures are considered acceptable. They propose systems based on head nodding and hand gestures on a touch screen, however, they do not evaluate their acceptability. Feldman et al. [24] propose ReachMedia, a system embedded in a bracelet to retrieve and navigate information related to physical objects. ReachMedia uses a short-range RF-id reader to retrieve information and recognize three hand gestures to navigate. The system can be operated hands-free and recognize gestures performed with very little movement. Marti and Schmandt [58] deal with the problem of mobile phone calls interrupting face to face conversations with a combination of sensing and subtle interfaces. Wearable, wireless networked sensor nodes detect face to face conversations among co-located individuals. If a phone call arrives to the mobile phone of someone engaged in a face to face conversation, all conversation partners receive a subtle notification through finger-rings that contain vibrating motors. The notification does not provide information about which of the conversation partners is receiving a call. The rings also contain a push button used to signal "unwanted interruption" — if any of the conversation partners presses the button this call is directed to voicemail.

In the WatchMe project [57] addresses remote awareness through mobile devices for a small group of close friends or relatives. Each member of the group has a wearable wristwatch device that senses his or her status through a variety of channels (such as GPS, acceleration and audio). This information is represented with a controllable level of abstraction, for example through the type of location (gym, bookshop) rather the exact geographic position, and constantly broadcasted to the rest of the small group. All members disclose the same type of information to each other, and when one looks at the status of one other, the latter is notified of this, as to communicate "X is thinking of you". The system also offer the option of "plausible deniability": the user can turn the sensing off and simulate being out of network coverage or being in a preset state. However in this system the interaction takes place through standard interfaces, so for example to be aware of someone else's status, and to let them know "I am thinking of you", users has to devote their full attention to a visual display.

1.3 Intimate Interfaces

This thesis presents the design and evaluation of novel interfaces and interaction techniques for mobile human computer interaction that are subtle, discreet and unobtrusive. In this context *Intimate Interafaces* are defined as interfaces that allow very personal and private interaction with mobile devices, addressing some of the issues described in this section. It has been suggested that wearable devices should be "as natural and (conceptually) unnoticeable as possible" if they are meant to be adopted in everyday and public situations [73], Intimate Interfaces extend this concept: not only should the devices be unnoticeable and natural, but also the interaction with them needs to be subtle, discreet and unobtrusive in order to gain social acceptance.

The concept of Intimate Interfaces is demonstrated in this thesis through the design, implementation and evaluation of two interface prototypes:

- **Intimate Communication Armband** — a wearable device, embedded in an armband, that detects subtle motionless input gestures through electromyographic (EMG) sensing and provides tactile output;
- **Notifying Glasses** — a wearable notification display embedded in eyeglasses; it delivers subtle cues to the peripheral field of view of the wearer — the cues can convey a few bits of information and are invisible to others.

Both devices take advantage of novel and essentially unexplored areas of investigation: EMG sensing of motionless gestures in a mobile context, and peripheral vision for non-disruptive notification.

The two devices do not occupy the users' hands, nor do they require hands for operation, hence they are "*hands free*." More generally, the interfaces take advantage of channels that are not often used — peripheral vision and brief contractions of a muscle — and they support multimodality. User studies on the fragmentation of attention in a mobile context suggest that these characteristics are beneficial for mobile interfaces in general, because they facilitate attention switching between mobile device tasks and real-world tasks [64].

Intimate Interfaces are designed to support *preliminary minimal interaction*: they allow users to receive notification cues and request more details about the notification source or just poll the mobile devices to check their status in a minimal, low attention modality. In this way users can acquire enough information to decide wether to ignore the notification or to interrupt their current principal activity (their *"primary involvement"* using Goffman's vocabulary [32]) and switch tasks, turning to a standard, higher bandwidth interface, such as a phone or PDA's visual display or speaker, or even the screen and keyboard of a laptop. Intimate Interfaces make information *available* to users without overwhelming them, and allow them to request more details when they want and when they can afford to dedicate more attention to it. This resonates with what was proposed by Weiser [85]: technology should be able to easily shift between the periphery and the center of the users attention.

Intimate Interfaces aim at *softening* (or *"calming"*, citing Weiser again [85]) the impact of constant connectivity through mobile devices. Users are already *inundated* with notifications and information, and it can be expected that this stream will grow thanks to emerging technologies such as location and proximity based systems, and the increasing bandwidth availability on mobile networks. Intimate Interfaces are designed to make information access not overwhelming, while still keeping it available. The introduction of such interfaces can, of course, become problematic, especially if they are used directly to consume or produce content, rather than to regulate access to higher bandwidth interfaces.

Interaction with Intimate Interfaces should be aimed at deciding whether or not to stop the current activity and attend to the mobile device, rather than to try and attend to multiple high attention demanding tasks at the same time (e.g. writing an email while conversing or driving). Low disruption can easily be interpreted as *secrecy*, Hansson, Ljungstrand and Redstr [33] suggest that for interruptions to be more socially acceptable they should be public, so that co-located individuals can more easily understand and accept the behavior of mobile technology users. The approach proposed with Intimate Interfaces is to leave to the users the decision about whether and how to inform those around them of the interaction with their mobile devices, starting from the observation that what is private can be filtered and made public, but not viceversa.

1.4 Usage Scenarios

Subtle intimate interfaces are meant to be used in a preliminary phase of the interaction: to allow users to minimally interact with the mobile system in order to understand whether or not to suspend their current activity and fully attend to the mobile system through a standard interface. This preliminary phase of interaction has to be designed to take into account that the users' attention might be engaged in other tasks, that these tasks might involve other individuals, or simply that users might be surrounded by co-located people who should not notice or be disrupted by the interaction.

An example scenario of such a preliminary interaction using subtle, intimate interfaces is as follows: Francesca receives a subtle notification about an incoming phone call while she is in a discussion with her boss Paolo. She decides not to interrupt the conversation and uses subtle input to reject the call and direct it to voicemail. This does not cost her much attention, so she can do it while still paying attention to Paolo's argument, or even while replying to him. Paolo does not notice the notification nor Francesca's reaction to it and he is not interrupted. Later on, while still in the meeting Paolo also receives a subtle notification about an incoming call. The cues conveys the information that it is his daughter calling. Knowing that his daughter is pregnant, Paolo apologizes to Francesca explaining that he's receiving an important call, he takes his mobile phone from his pocket (a standard interface) and answers the call.

Most of the interaction with mobile devices takes place in a social context when surrounded by other people. If a mobile phone rings during a face to face conversation most likely the call will be ignored and returned later. In this case the phone ringing is an unnecessary and unpleasant distraction. Vibrating alerts provide a certain improvement, but they are often still audible which makes them as distracting as ring tones. In comparison, notifications from the Notifying Glasses do not disrupt the people around us and can easily be ignored. If the system also includes the EMG-based Intimate Communication Armband, users can not only be subtly notified, but they can also react to the notification in a subtle, unobtrusive way; for example, rejecting the incoming call by briefly contracting the upper arm.

The importance of subtle, unobtrusive and non-distracting notification cues is made even more relevant by location-based and proximity-based services, which are receiving more attention from both the academic and business communities. Many of these systems provide relevant information when users are in physical proximity of an object [24] or place of interest [79]. In these scenarios, subtle cues, such as the ones provided by the Notifying Glasses, can let users know about available information without distracting them or disrupting the people in their environment. If desired, users can visualize the full piece of information through some other device (PDA, phone, foveal eyeglass display, earpiece, etc.).

As an example scenario, imagine Marco is running late for a business meeting, and he's walking fast towards an underground stop on the way to his office. When he passes in front of a bookshop he receives a subtle cue from his location-aware mobile phone. The cue indicates that there is some relevant information related to shopping. He imagines that a new book matching his interest profile must have recently arrived at the bookshop, however he has no time to stop now, so he ignores the cue and keeps walking. When he is closer to the underground stop he receives another notification cue; this one informs him that some information about transport is available. Knowing his own context, he wants to know more, so he takes his mobile phone out of his pocket (a standard interface) and reads an alert, from its large high contrast display, saying that because of unplanned maintenance, the undergrounds service is suffering from significant delays. He then stops a cab to go to the office.

1.5 Outline

This thesis is divided into four parts. The first part (this chapter) provides a general introduction to Intimate Interfaces, framing their definition within sociological observations and prior research in mobile HCI. The concept is then demonstrated through the design, implementation and usability evaluation of two Intimate Interfaces: the *Intimate Communication Armband* and the *Notifying Glasses*, presented respectively in the second and third parts of this thesis. For each interface, *related work*, *system design & implementation* and *evaluation through user studies* are described in separate chapters. Finally, the fourth part of the thesis presents conclusive remarks about Intimate Interfaces in general.

Part II

Intimate Communication Armband

Chapter 2

Background: Electromyography and Tactile Displays

This chapter introduces previous research related to the Intimate Communication Armband: electromyographic sensing and its applications, particularly within the HCI domain, and tactile displays. It must be underlined that no prior work exists on the use of electromyographic sensing of subtle gestures.

2.1 Electromyography

The electromyographic (EMG) signal is an electrical signal generated by muscle contraction. Methods for effective recording and computer aided analysis of EMG signals have been the object of study in the field of biomedical engineering for the last three decades [50]. Through electromyography it is possible to sense muscular activity related to movement, but also *isometric* activity: muscular activity not that does not produce movement [77]. An example of isometric activity is pushing against a wall, muscles are activated, but the wall prevents movement, similarly, isometric activity can be produced by flexing the muscles without load, as when "showing off muscles". As detailed in Chapter 3, the sensing of isometric activity has great potential for mobile interfaces.

The EMG signal can be recorded non-invasive using surface electrodes, or through needle electrodes. Needle electrodes produce better signals because they are in close contact with the source. While their use can be justified for medical applications, in a non-medical context, such as the ones considered in this thesis, they would be highly impractical for the discomfort caused to the user. Moreover, the advantages of needle electrodes are reduced by current integrated circuit technology, that makes it is possible to connect high gain, low noise amplifiers very close to the electrodes, thereby producing usable EMG signals from surface electrodes, at least for the application considered in this thesis. In the rest of this document it will be assumed that the signal is always acquired through surface electrodes, applied in differential pairs, each pair constituting a channel.

The EMG signal is the result of the superposition of electric voltage generated by each motor unit in a muscle. The use of surface electrodes records from a large number of motor units per each channel, as a consequence, the resulting EMG signal can be represented as a signal with Gaussian distributed amplitude, topically ranging from 100 μV to about 1 mV [50].

Commercial surface electrodes are generally Ag/AgCl plates attached to the skin with adhesive and covered with conductive gel (often solid gel for increased comfort). The gel is used to improve the electrode to skin interface lowering the impedance seen from the sensor, and reducing motion artifacts. *Active* or *driven* electrodes are sometimes used to create a feedback control loop between the sensor and the body [84], this method also reduces motion artifacts eliminating the need of conductive gel: in this case the electrodes are referred to as *dry*. Advances in material technology are producing surface electrodes in forms that can be more comfortable for consumer use, for example, electrodes embedded in flexible grids [47] or even embedded in fabrics [66].

The typical biomedical analysis for diagnosis applications involves envelope detection, energy measurement (directly related to the force) and frequency characterization [51]. Control applications generally involve signal acquisition from a number of differential electrodes, feature extraction and real-time pattern classification. The first examples of EMG based real-time control systems can be found in the field of prosthesis control and functional neuromuscular stimulation. Hefftner et al. [37], for example, report successful results from a system that can recognize two gestures generated from the shoulder and upper arm. The system must be specifically calibrated for each subject and uses EMG signals from two channels.

Recently Lukowicz et al. [52] presented a system based on wearable force sensitive resistors to sense muscle activity. They show a correlation between the mechanical deformation of the limb (measurable through force sensors placed on an elastic band adherent to the body) and muscle activity, especially fatigue. This approach allows the recording of activity that cannot be obtained through inertial sensors. Their approach is very interesting but it was not tested on pure isometric activity recognition.

2.2 EMG for Human-Computer Interaction

A number of studies focused on the use of EMG signals for computer interfaces targeted at users with physical disabilities. Putnam and Knapp [71] developed a reconfigurable system to control generic graphical user interfaces. The system incorporates a continuous control mode where the amplitude of the contraction is mapped to a parameter swing (sliders, scrollbars) and a gesture recognition mode that discriminates between two gestures and can be used for discrete selections. The gesture recognition is performed on a dedicated digital signal processing (DSP) board and is based on neural networks. In addition, it requires training for each user of the system. Barreto et al. [6] propose a system to control a mouse-like point and click interface using facial muscles. Spectral features of EMG signals are analyzed, in addition to the amplitude, to increase performance. The system is not reported to require individual calibration for each user and it is implemented on a DSP board.

Other examples of EMG based HCI include a number of interfaces for musical expression. For this type of application the signal is used in a continuous fashion (rather than performing gesture recognition), the amplitude is mapped to a variety of sound synthesis parameters. The systems presented in this context are often wearable and allow movement of the performer on stage, yet they are not (explicitly) designed for the mobile (everyday) context. Knapp and Lusted [46] present a generic battery powered platform to interface EMG signals to MIDI systems. Tanaka and Knapp [77] complement EMG data with inertial sensor information, so that both isometric (muscle tension resulting in no motion) and isotonic (motion with constant muscle tension) activity can be monitored. Dubost and Tanaka [22] developed a wearable wireless musical controller supporting pre-processing of EMG signals and output interfacing with different standards (MIDI, RS232 and Ethernet). Their system requires calibration for every user.

Recent studies focus on the use of EMG for the recognition of an alphabet of discrete gestures. Fistre and Tanaka [43] propose a system that can recognize six different hand gestures using two EMG channels on the forearm. The device is designed to control consumer electronics and is described as portable. Testing in a mobile context has not been reported. Wheeler and Jorgensen [86] report the development and successful testing of a neuroelectric joystick and a neuroelectric keypad. Using EMG signals collected from four and eight channels on the forearm they successfully recognize the movement corresponding to the use of a virtual joystick and virtual numeric keypad. Gestures mimicking the use of physical devices are successfully recognized using hidden Markov models. The system is proposed as an interface for mobile and wearable devices, but an embedded implementation is not reported, nor is testing in a mobile context.

In a different fashion, but still in the context of HCI, EMG signals have been used in conjunction with other physiological signals (skin conductivity, blood pressure and respiration) to detect the affective state of the user [36].

2.3 Tactile Displays

Tactile displays use a variety of techniques to stimulate the human sense of touch, including piezo-electric actuators [69], vibrating motors (also known as "pager motors") [31] or audio-like loudspeakers[76]. Tactile stimuli, especially if in unusual patterns, are highly attention demanding [28](discussed in [69]), therefore, tactile display are commonly used for notification, as in most commercial mobile phones. However, the tactile channel can be used for higher resolution communication, using variations in the intensity, frequency, duration and location of the stimuli. The use of tactile displays in the context of mobile devices has been advocated by several authors [69, 31, 76].

Tan and Pentland [76] propose a directional display with nine actuators distributed in 3-by-3 grid on the back of the user. The actuators are flat magnetic speakers modified to resonate at low frequencies. The display was conceived to be wearable and to take advantage of the "sensory saltation phenomenon", a perceptual phenomenon that allows to "simulate higher spatial resolution than actual spacing of stimulators, yet mimic the sensation produced by a veridical set of stimulators with thes same higher-density spacing"[76]. Gemperle et al. [31] designed a wearable tactile display for navigation guidance based on an array of vibrating motors distributed over the body. Gemperle et al. plan user studies to validate the design, but no results are reported. Poupyrev et al. [69] reported the design of a novel small, low voltage, fast response actuator based on layers of piezoceramic film. The actuator is embedded in a commercial PDA and used to provide feedback for gesture recognition. Experimental results show that the novel display is effective and improves the performance of subjects controlling the gestural interface.

Vibrating motors have been often criticized for their limited expressive capabilities, especially compared to other actuators [69]. However, results from recent studies show that it is possible to convey different messages through amplitude modulation of sinusoidal driving signals. Brown et al. [10] report upt to 93% recongition rate for characteristics of "tactons", tactile icons, using a high specification transducer in controlled conditions. Brown and Kaaresoja report that even better results (up to 95% recognition rate) can be achieved using the vibrating motor of a standard mobile phone [11].

Chapter 3

Design and Implementation

The first Intimate Interface prototype is the Intimate Communication Armband. Its design and implementation are described in this chapter. The process was carried out in an iterative fashion and validated through users studies, as detailed in Chapter 4.

3.1 Design

The Intimate Communication Armband was conceived as a generic input/output peripheral for mobile devices. It is worn on the upper arm, invisibly under clothes (Figure 3-1, and senses explicit subtle gestures and provides localized tactile output. The Intimate Communication Armband connects wirelessly via Bluetooth to a phone or PDA, sitting in the user's pocket or bag. Being a generic i/o device, it emits signals every time a gesture is recognized and it accepts signals to activate the tactile display. The mapping strategy to connect these signals to specific interface actions and events is left open to the application designer.

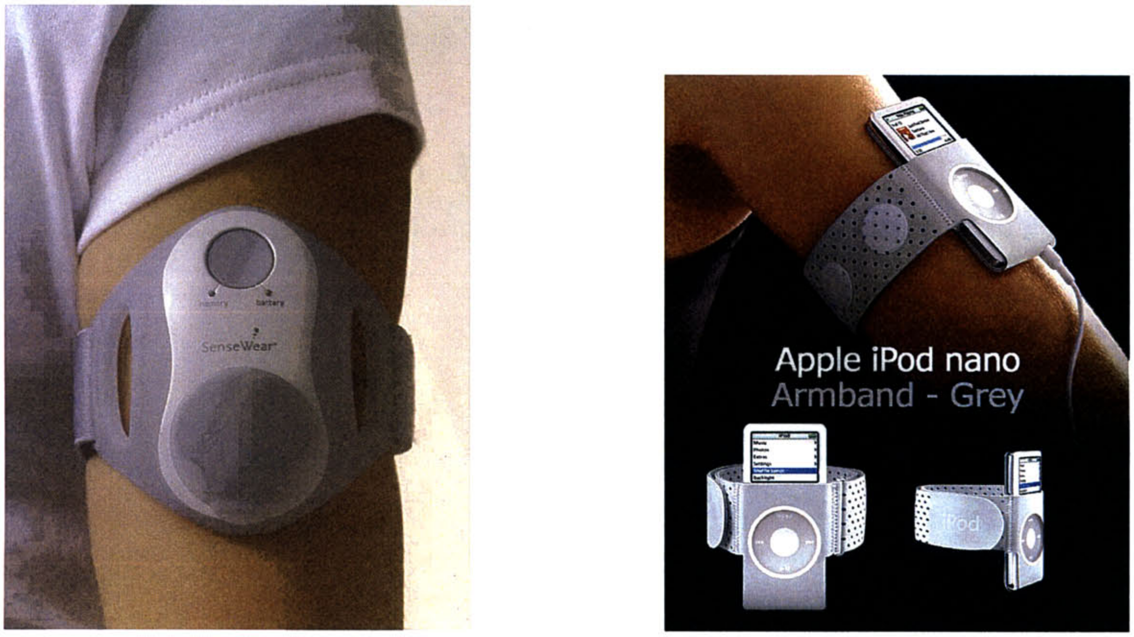
The Intimate Communication Armband does not occupy the users hands, and does not require them to operate it, hence it is hands free. On its own it can be used for minimal communication or remote awareness, as discussed in the first chapter. However, its greatest

Figure 3-1: The Intimate Communication Armband can be made invisible by hiding it under clothing.

potential is realized when combined with a higher resolution hands free display — such as headphones or loudspeakers or even high resolution eyeglass displays — so that it forms a closed loop hands free system. This can be highly advantageous in a number of everyday situations, for example when the user is carrying objects, or for specific domains of applications, such as maintenance, where the users hands are needed to perform a principal task, and the mobile computing system is used for assistance. For example, an audio guide could be read through headphones and an armband could be used to advance, pause or rewind the system. The tactile display can be used to give feedback about a subtle gesture being recognized, or it can deliver alerts and notifications, even though tactile notifications require much attention (cfr. Section 2.3).

The concept behind the Intimate Communication Armband aims for wide acceptance as a consumer electronic device. The design takes inspiration from the BodyMedia SenseWear device, a commercial device used for monitoring of biosignals for health applications (Figure 3-2 a) , and at common wearable digital music players (Figure 3-2 b) , worn on the upper arm when users practice sport.

From a technical point of view, the major challenge in the realization of the intimate communication armband is the sensing of subtle motionless gestures. Standard "pancake" vibrating motors are used for the tactile display. Even though more complex tactile actuators could provide additional expression capabilities, basic vibrating motors offer a simple, yet effective solution. Conversely, no readily available solutions existed for the sensing of



(a) (b)

Figure 3-2: (a) The Bodymedia SenseWear armband is a consumer electronics product for personal health monitoring. (image from www.bodymedia.com)
(b) An armband to wear the Apple iPod digital music player. (image from www.taoriver.com)

motionless gestures, as this is a novel and essentially unexplored field.

3.1.1 Motionless Gestures

The definition of a class of subtle or motionless gestures is based on the EMG signal's ability to detect isometric muscular activity, i.e. muscular activity not related to movement. Motionless gestures are defined as specific, isolated and explicit muscle contractions that do not result in visible movement. For practical reasons only the subset of gestures that can be distinguished from everyday muscle activation patterns. Previous studies on the use of EMG for human computer interaction (mobile or not) do not explicitly consider subtlety, leading to a different approach. Tanaka and Knapp [77] report as a limitation the fact that in EMG signals muscular activity and movement are not always related. They remedy this by complementing EMG with inertial sensor (gyros) data in a multimodal fashion. Fistre and Tanaka [43] and Wheeler and Jorgensen [86] propose the use of EMG for hand gesture recognition as an alternative to accelerometers or mechanical sensors for movement, but not for subtle gestures.

Compared to other EMG based systems [43, 71, 86] the approach proposed here is to trade resolution in terms of variety of gestures being recognized for:

- minimizing computational complexity
- robustness against false positives
- use of only one input channel
- avoiding calibration or system training for each user

Minimal computational complexity is essential to implement the real-time processing in a low power embedded device, such as an 8-bit RISC microcontroller.

When compared to other types of sensing EMG presents a number of difficulties due to the need for contact electrodes and their placement [73]. However, the advantages it provides related to subtlety make it worth studying. Moreover, research in smart materials (cfr Section 2.1) and non-contact sensing [80] are even more encouraging.

The system design was carried out as an iterative process centred on users. A number of exploratory informal user studies were performed to insure that the system would be natural and easy to use. Figure 3-3 summarizes the process.

As detailed in Section 2.1, the EMG signal is a bio-potential in the range of 100 μV to about 1 mV. The general system design for the subtle gesture sensor is illustrated in Figure 3-4 and it includes:

- surface electrodes to pickup voltage signals on the body
- signal amplifier and analog preconditioning stage
- analog to digital converter

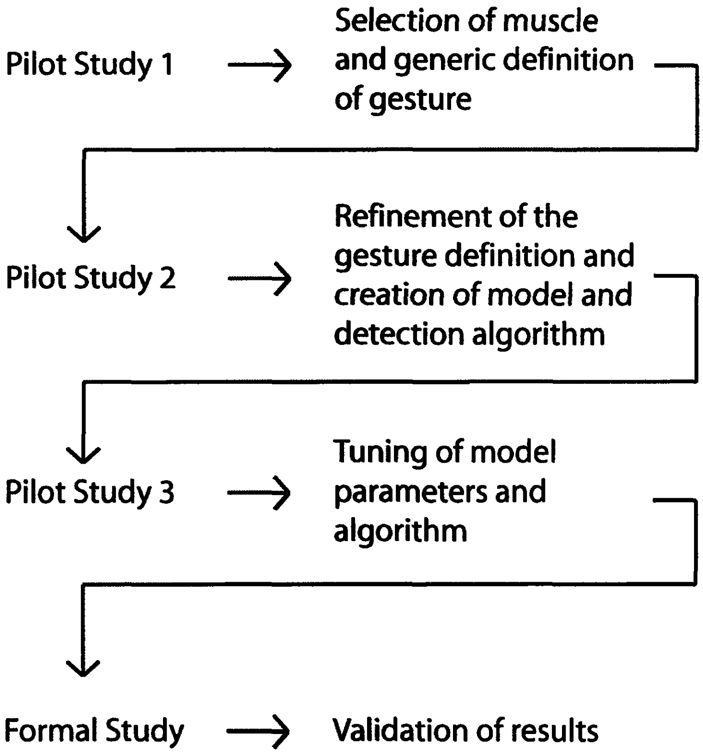


Figure 3-3: Outline of the design process for the subtle gesture recognition.

- digital pattern recognition system
- interface with application on mobile device or PC

The signal preconditioning was performed through analogues rather than digital filters to keep the complexity of the digital processor low. This choice was made based on the low computational cost of the detection algorithm, which can run on a low-power 8-bit RISC microcontroller. The use of a more complex detection algorithm would probably justify the use of separate DSP chip or more powerful microcontroller, which could also handle the signal preconditioning.

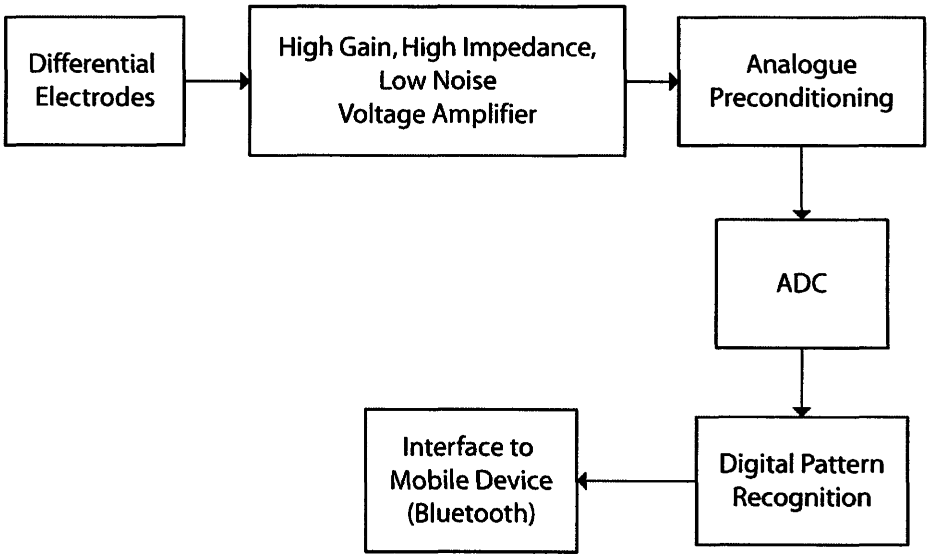


Figure 3-4: Block diagram for the EMG subtle gesture recognition system.

3.2 Implementation

3.2.1 First Prototype

The first version of the system was developed at Media Lab Europe, in collaboration with Samuel A. Inverso, Alberto Perdomo, Juan Jose Andres Prado and the support of Matt Karau. The first EMG sensor hardware prototype was based on an Electro-EncephaloGram (EEG) amplifier board developed at Media Lab Europe by the MindGames group for the Cerebus project. An AVR AT Mega8 microcontroller was used to sample the signal and transmit it via serial over Bluetooth to a host computer. An extra amplifier stage was designed to adapt the output of the EEG amplifier to the AVR Analog to Digital Converter (ADC) range. The AVR serial output was connected to a PROMI-ESD Bluetooth module manufactured by Initum [41]. The system was powered from 3 rechargeable 9V batteries. Because of their weight, the batteries could not be comfortably worn on the upper arm, so they were connected with long wires and housed on a pocket worn around the waist. The amplifier and microcontroller boards, as well as the Bluetooth module, but not the batteries were housed in a box, illustrated in Figure 3-5

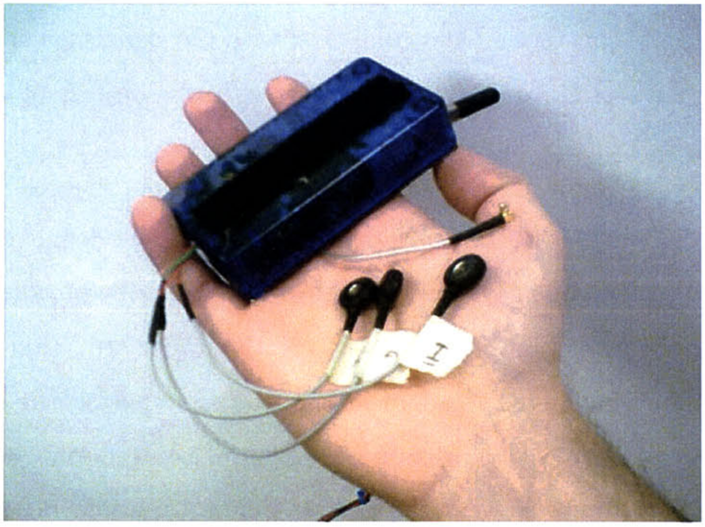


Figure 3-5: The first EMG sensor prototype (excluding batteries).

The design of the recognition algorithm and the definition of the gesture were carried out in parallel to satisfy two requirements: the gesture should be (1) natural for people to perform, and (2) different enough from normal muscle activity to avoid misclassification or false positives.

The process started with a pilot study to select one muscle and subtle isometric contractions that could serve the definition of motionless gestures. The subjects for this pilot were chosen so that a range of different muscle volumes were tested. Initial candidates for the muscle selection were: the temporalis, the biceps, the triceps, the forearm, the abdominals and the calf. Factors considered for the decision included: ease of electrodes placement, quality of the acquired signal and the type of activity that each muscle contributes during normal movement, such as walking. The test revealed the biceps as the best candidate because it lies superficially making the signal fairly immune to activity generated by other muscles, and it is well defined even in non-athletes. The gesture was defined as a brief contraction, such that it could be performed without being noticed, while the arm is unfolded, parallel to the body while the user is standing.

A second informal study was conducted to refine the definition of the subtle gesture and create a model and algorithm for its detection. New subjects participated in the study and were chosen for a variety of muscle volumes. EMG signals were recorded from subjects performing the selected contraction and compared with the signals generated by other types of muscle activity, such as moving in an indoor space, lifting objects of various weights and gesticulating while talking.

The subjects were informed that the purpose of the study was to define a subtle gesture that could be used to control mobile devices. The gesture was described to them in a not detailed way (just as a "brief contraction of the biceps, i.e. the upper arm, that would not be very evident") so that they had some freedom in the way they performed it. This procedure aimed at exploring whether such a definition of "brief contraction" would be consistent across individuals, and to ensure that the gesture definition would be, to a certain extent, natural to perform, rather than defining a gesture a priori and ask or force the users to learn it.

3.2.2 Subtle Gesture Model

The model resulting from the second study, depicted in Figure 3-6, is based on the standard deviation of the EMG signal, calculated with a sliding window of duration 0.2s overlapping for 75% of its duration. The standard deviation was chosen to smooth the data and emphasize discontinuities in the energy of the electromyogram. The window size was selected to be the longest possible without filtering out interesting features. A mathematical model and a recognition algorithm for the brief contraction were then created heuristically from the observation of the data. A brief contraction was observed to correspond to a peak in the standard deviation of the signal. Given the noise-like characteristics of the EMG signal [50], standard peak-detection techniques could not be employed. Rather, such peaks were modeled as follows: a "beginning" interval of duration T_B of low activity ("silence") followed by a "middle" interval of high activity of duration T_M and then again low activity for an "end" interval of duration T_E. High activity and low activity were defined respectively as the standard deviation of the signal being above a threshold H and below a threshold L. To allow some tolerance in the model, the condition on the history is imposed on the average of its values. The condition on the middle needs to be satisfied by 50% of the samples, and the condition on the end by 70% of the samples.

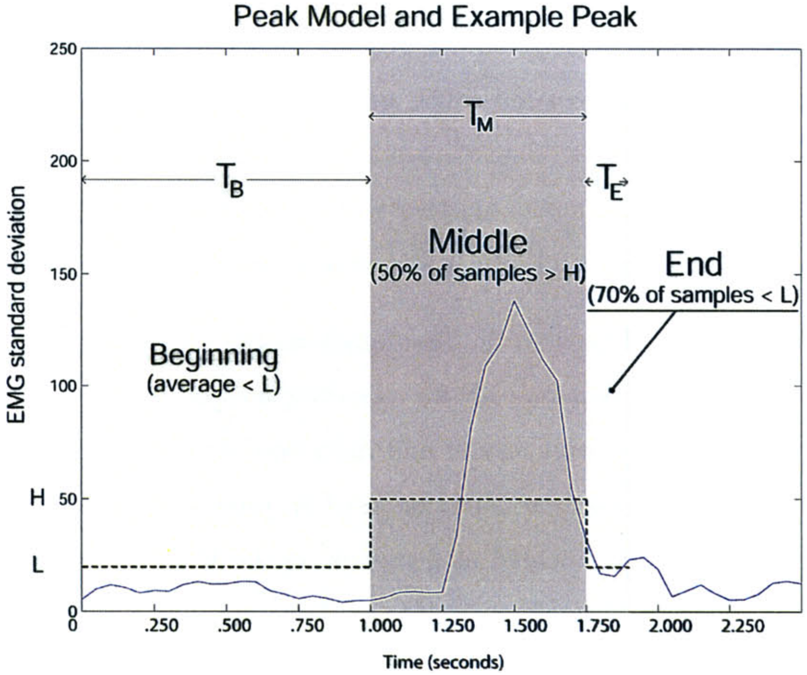


Figure 3-6: Model for the subtle gesture, and example gesture recording detected by the algorithm.

The model definition is more strict on the duration of the contraction than it is on the gesture's intensity. This is because the preliminary study showed that the duration was more consistent than the intensity across users, despite the fact that no specific indication was given about either. One disadvantage of this model is that it requires the gesture to be completed before the recognition can take place. The recognition could be made faster by removing the end condition for the closure of the gesture; however, this would cause an increase in the number of false positives.

The tuning of the five parameters of the model required a third informal study. New and returning users were informally asked to test the system. The testing was conducted to stress the system to produce false positives and false negatives. The iterations continued until the number of false positives approached zero and the system recognized contractions performed by any user.

3.2.3 Two Gestures: *Long* and *Short*

Once the recognition worked robustly on one gesture, the possibility of creating a gesture alphabet of two gestures was explored. The gestures were defined as two short subtle contractions of different durations. This corresponded to varying the value of the duration of the middle interval T_M in the model together with its tolerance. The results obtained at this point were then validated with the first formal user study, described in Section 4.1.

For the development of the algorithm, the raw signal sampled at 80 Hz was streamed to a 2GHz Pentium 4 PC running Windows XP for recording and processing. The data analysis and the development of the gesture model and detection algorithm was then performed off-line using Matlab. The real-time detection used to provide feedback to the subjects during the user study was implemented as a module in the BCI2000 software framework [74], rather than on the embedded device itself to to allow real-time monitoring of the EMG signal and classification output for the experiment.

3.2.4 Second Prototype

The first hardware prototype was extremely useful to show that it was possible to recognize subtle motionless gestures through EMG signals, but it had a number of limitations. The EEG amplifier used was not easily replicable, because based on a 4-layer board, which required external manufacturing and because the design documentation was not always easily accessible. In general, the performance and dimension of the system were suboptimal, as it was assembled from circuits originally designed for other purposes and required supply from bulky batteries. Therefore, the need for a second hardware iteration was immediately clear. A full system redesign was initiated at Media Lab Europe by Alberto Perdomo and Juan Jose Andres, however, this was completed shortly before the lab closure, so the resulting system was not available to the author of this thesis for continuing the research. A separate re-design was then started at the MIT Media Lab.

To limit interference between the analog and digital parts of the circuit, two separate Printed Circuit Boards (PCB) boards were designed, and the analog and digital grounds connected only in one point, between the analog board output and the ADC input. The new amplifier design was based on a portable ElectroCardioGram (ECG) sensor [15]. The system uses an integrated instrumentation amplifier in the first stage with a right leg driver feedback stage to reduce noise. The right leg driver is a quite common design in biosignal amplifiers [84]. After the first stage a 1st order high pass filter at 1.6Hz is used to eliminate DC components followed by a 2nd order Sallen-Key active low-pass Butterworth at 48Hz with a gain factor of 10. This stage performs further noise reduction and anti-aliasing for the digital conversion. A final stage with unity gain is used to offset the signal by 1.6V, centering it with respect to the ADC range. An LM2685 "Dual Output Regulated Switched Capacitor Voltage Converter" from Analogue Devices was used to provide the +5V and -5V supply for the analogue stage from a single cell 3.7V, 130mAH Li-Po battery used to power the device. The circuit schematic is illustrated in Figure 3-7.

An Atmel 8-bit AVR microcontroller was again used for analog to digital conversion, gesture recognition and to drive the vibrating motor included in the second prototype. The motor was driven through Pulse Width Modulation (PWM) to allow fine tuning of the vibration intensity. The microcontroller used in this case was the more recent and power efficient AT Mega168. The PROMI-ESD Bluetooth module was replaced with the BlueGiga WT12, a smaller surface mount module that provides a flexible and simple software API. The "High Accuracy, Low Dropout" ADP3330 voltage regulator by Analogue Devices was used to convert the battery voltage to the 3.3V required by the Bluetooth module and provide a stable supply for the microcontroller. The board also included a C-MOS driver and a protection diode for the vibrating motor, and two LEDs for displaying the microcontroller status during debugging.

The two boards and the battery were housed in a box of about 3cm x 4cm x 2cm, which was inserted into an elastic armband made for a commercial MP3 digital music player, as shown in Figure 3-8.

The aim for the second prototype was to get the recognition running fully on the embedded

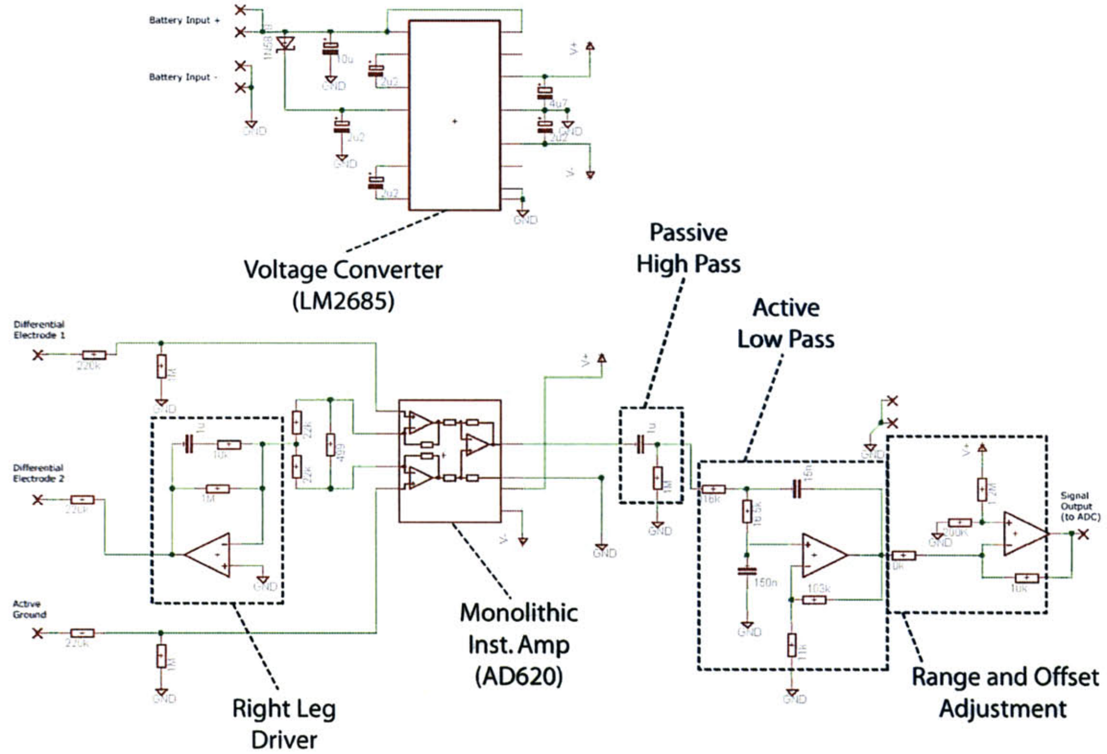


Figure 3-7: Circuit schematic for the second generation EMG amplifier.

microcontroller. For the development phase, the raw signal was again streamed to a PC. To remove the dependency from BCI2000, which is unnecessarily complex for the task, the gesture recognition was initially ported on the Linux PC platform in C, using a C++ software framework for data acquisition over serial port (and serial over Bluetooth) and real-time processing developed by the author. This framework allowed software development in an environment more similar to the embedded platform and based on the same GNU C compiler, but still allowing easy debugging.

The algorithm was implemented using accumulators and FIFO buffers to calculate the moving average and variance; this was used in place of the standard deviation to save a square root operation. The sampling rate was set to 160Hz, so that the 0.2s sliding window used for the average and variance (same duration as in the first prototype) corresponded to 32 samples and divisions could be replaced with bit shift operations. The main difficulty in porting the pattern recognition code to the AT Mega168 was reducing the usage of RAM

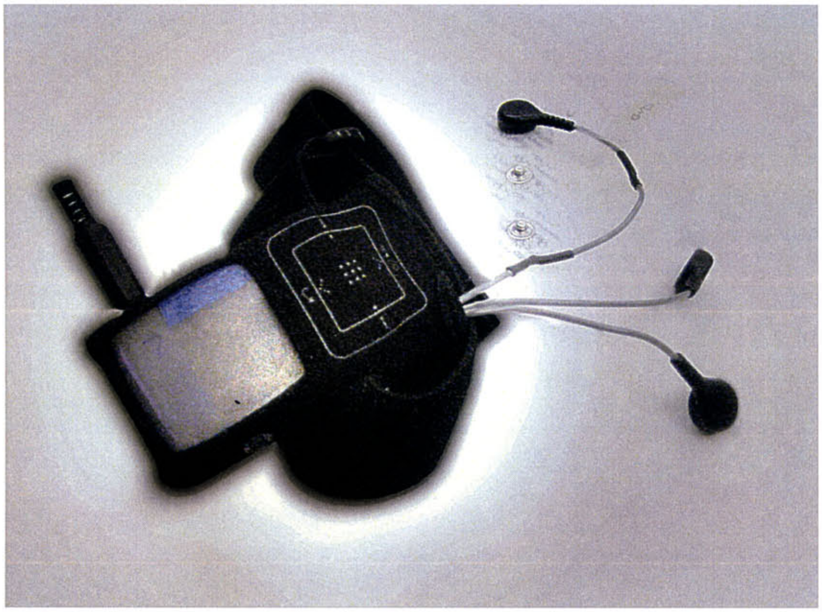


Figure 3-8: The second generation EMG sensor inside an armband holder for a commercial digital music player. The connector on the left of the photograph is used for recharging the battery and also as a power switch.

to the amount available on the microcontroller. This required the careful selection of the data types (8-bit, 16-bit or 32-bit integers) to match the precision of the data.

In the advanced stage of development, it was noticed that motion artifacts could produce false positives, visual inspection of the signal recording showed that the artifacts produced low frequency fluctuations not removed by the analogue high-pass filter. To reduce the number of false positives a simple zero-crossing counter was included in the detection algorithm, a detection was recognized only if 10 or more zero crossings occoured over its duration (the threshold value was found by trial and error with two subjects).

Chapter 4

Evaluation

Three user studies were performed to validate the design of the electromyographic (EMG) motionless gesture sensor and more in general of the Intimate Communication Armband. The first study was aimed at assessing the very basic functionality of the EMG-based controller: can the device reliably recognize gestures? Is it natural for people to perform the gesture? Is the gesture easy to learn? Therefore, in the first study subjects were initially asked to play with the device and familiarize themselves with it, subsequently they were asked to perform a gesture every time they were prompted through an audio stimulus. The gestures had to be performed while subjects were involved in a realistic, but safe mobile task. Results from this first study showed that subjects quickly learn to reliably control the device with little or no training, and that the system can reliably recognize the gestures (96% correct detection). The following step was to study more complex interaction scenarios. In a second study subjects interacted with an audio menu through subtle gestures. Two conditions were compared: controlling the menu with just one armband controller or with two controllers, one per arm. To experimentally test how visible the gestures are to others, the same subjects observed a video clip of a trained user activating the system and were asked to report when they believed the person in the video was performing a gesture.

4.1 Initial Study: Basic Gesture Recognition on Dominant Arm

The first experiment was designed and run in collaboration with Samuel Inverso at Media Lab Europe [18].

4.1.1 Experimental Design

Subjects performed five walking tasks using the wireless EMG device, one without contracting (to determine the devices misclassification rate), and four while making contractions of different durations. Each of these four contraction tasks was preceded by a short familiarization session. While walking, participants navigated 24 meter laps around obstacles setup in a regularly trafficked walkway in Media Lab Europe, see Figure 4-1. This setup was similar to the one reported by Pirhonen et al. [68] who noted this mobile context allows us to "take measurements of the usage of the device whilst the users were mobile but was not as formally controlled as a laboratory study, which would lack realism and ecological validity."

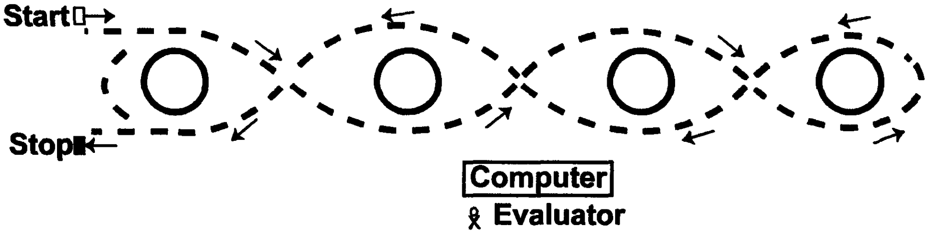


Figure 4-1: Route walked by the subjects.

Subjects were given written instructions that informed them the study was assessing EMG as a subtle interface for mobile devices and they would control the system using their biceps while walking using a subtle contraction that could be performed with their arm relaxed at their side. Subjects were also informed that the contraction recognized has a minimum and maximum duration and a minimum strength requirement. No further instructions were given for the subtleness of the contractions, thus it was subjective to the participant to define subtly.

During each of the contraction tasks participants were prompted to contract with an audio stimulus in the form of a MIDI piano tone delivered through wireless headphones. The four contraction tasks are referred to as 'generic', 'short', 'long', and 'mixed' contractions. In the generic task participants attempted to consistently make contractions that the system would recognize. In the short task they attempted to consistently make the shortest contraction the system would still recognize. In the long task they attempted to consistently make the longest contraction the system would recognize. In the mixed task they attempted to make both long and short contractions when given corresponding stimuli. Each task was preceded by a short familiarization session. During the familiarization sessions participants stood and only heard an auditory feedback when the system recognized a contraction. No coaching or further feedback as to the amplitude or duration of the contraction was given to the participants, so they were unaware of why the algorithm was or was not recognizing the contraction. They were only aware if the contraction was recognized. This was also true for the walking tasks.

In all contraction tasks the same real-time detection algorithm was used across participants without calibration or modification, and it recognized contractions of duration between 0.3 and 0.8 seconds. If the system detected a muscle contraction participants were given auditory feedback in the form of a MIDI trumpet tone delivered through wireless headphones. No further feedback was given, thus when performing contractions participants were quantitatively unaware of the contraction's duration. This minimal feedback was given to establish if the subjects could learn to use the feedback without specific training.

Subjective workload was measured with the NASA TLX [35] scales after each walking contraction task to assess demands imposed by the EMG controller and the different contraction types. Workload is important because in a mobile environment users have less attention to spend on the interface and interaction technique because they are monitoring and navigating their surroundings [68], an additional complexity is introduced when the interaction technique uses the same body parts used while mobile. Therefore, an interface and interaction technique with a lower workload will be more successful in a mobile context.

For the system setup, the participants skin was first prepared with an abrasive gel to ensure signal quality. In pilot studies, it was found that pre-gelled electrodes did not require skin abrasion unless users had applied skin creams or lotions earlier in the day. For consistency, all participants were abraded in this formal study. After abrasion, disposable, sold-gel, self adhering, Ag/AgCl 9mm disc surface electromyogram electrodes were applied in three positions around the upper arm of the subject's dominant hand such that the one of the differential pair electrodes was centred on the biceps brachii, the other differential electrode was on the inside middle of the upper arm below the biceps, and ground was placed on the middle outside of the upper arm see Figure 4-6. The electrodes were placed around the upper arm to test the feasibility of embedding them in an armband. For participants 1, 2, and 4 the reference and ground positions were swapped because the inner reference pressed against their bodies while walking causing deflection artifact.

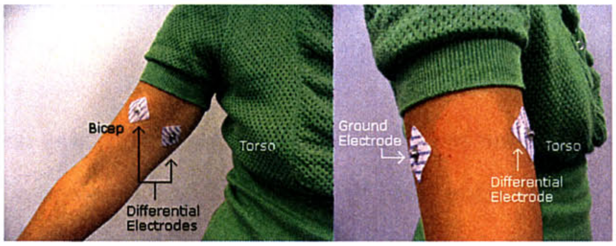


Figure 4-2: Electrode placement used for the first user study.

After the electrodes were applied, the wireless EMG device was mounted to the upper arm with an elastic band between the electrodes and elbow. The wireless EMG device streamed 10 bit values at 80 Hz over serial Bluetooth to a 2 GHz Pentium 4 PC running Windows XP. The BCI2000 software framework [74], running on the PC, was used for signal processing and stimulus presentation. While the contraction detection algorithm was simple enough to run on the device's micro-controller, it was implemented under BCI2000 to allow real-time monitoring of the EMG signal and classification output for the experiment.

4.1.2 Tasks

All subjects participated in all tasks: within-subjects design. The tasks proceeded in order as follows, however, the short and long contraction tasks were performed in counterbalanced order, such that a participant randomly performed short or long first. The tasks in detail are:

1. **Walking, No Contractions:** While wearing the wireless EMG device participants were instructed to walk ten laps at their preferred walking speed.

2. **Standing, Familiarization, Generic Contractions:** Participants were given the wireless headphones, and told to briefly contract their biceps freely in order to familiarize themselves with the system. The familiarization ended when either the participant was confident interacting with the system or a fifteen minute time limit was reached. If participants could not confidently use the system after the time limit they were verbally given feedback as to why their contractions were not controlling the system. This was only necessary for participants 2, 9, and 10; who were only told once to shorten their contractions, and then they were quickly able to control the system.

3. **Walking, Stimulus-Response, Generic Contractions:** Subject's walked the obstacle course and attempted to contract when they heard an audio stimulus through the wireless headphones. Participants were randomly presented 15 (SD=5) stimuli.

4. **Standing, Familiarization, Short Contractions:** Similarly to generic contraction familiarization, participants stood and only heard an auditory feedback when the system recognized the contraction. The system recognized the same contraction duration as in the first two tasks; it was subjectively up to the participant to define the short contraction. Participants were again instructed the system recognized a contraction of certain duration and they should explore the limits of the system. When they were comfortable making the shortest contraction they thought the system would still recognize the experiment continued with the next task.

5. **Walking, Stimulus-Response, Short Contractions:** Participants walked the obsta-

cle course again and attempted their short contraction when they heard an audio stimulus through wireless headphones. Participants were randomly presented 15 (SD=5) stimuli.

6. Standing, Familiarization, Long Contractions: Participants stood and only heard an auditory feedback when the system recognized the contraction. The system recognized the same contraction as in the previous tasks, it was subjectively up to the participants to define the long contraction. When they were comfortable making the longest contraction they thought the system would still recognize the experiment continued with the next task.

7. Walking, Stimulus-Response, Long Contractions: Participants walked the obstacle course again and attempted their longest contraction when they heard an audio stimulus through the headphones. Participants were randomly presented 14 (SD=3) stimuli.

8. Walking, Stimulus-Response, Mixed Long and Short Contractions: Finally, participants were instructed to walk the obstacle course again and make both short and long contractions when they heard either a high pitched MIDI piano tone (short contraction) or low pitched MIDI piano tone (long contraction) stimulus. Participants were randomly presented 23 (SD=5) total stimuli: 12 (SD=3) short and 11 (SD=3) long.

4.1.3 Description

Participants were 10 adults: 5 women and 5 men, ages 23 to 34, all were colleagues from Media Lab Europe who volunteered for the study. Subject 8 participated in a pilot study; all others were naive.

4.1.4 Results

No false positives were detected while on-line during the first walking task. In addition, the on-line recognition rates for the four contraction walking tasks were: generic 96%, short 97%, long 94%, and mixed 87%.

In the first familiarization task, participants were able to control the system in an average of 3.75 minutes (SD=2.17), excluding the three participants who reached the fifteen minute time limit and required additional feedback. The participants given feedback (2, 9 and 10), all had the same difficulty that their contractions were too long. They were told once to make their contractions shorter and then they were able to control the system in 11.75, 1.78 and 5.48 minutes respectively.

As mentioned in the Design Process, offline analysis was performed on the data from the short and long contraction walking tasks to determine if short and long contractions are separable into two gestures for control. Figure 4-3 shows the mean and standard deviations for the short and long contraction durations. From the data, a duration boundary of 0.5 seconds was used to create a new recognition algorithm that recognized long and short contractions separately. As with the original algorithm, only the first recognition was counted, any additional recognition was ignored until the next stimuli. Applying this new short-long detection algorithm to the mixed contraction data resulted in an overall accuracy of 51%, with 55% shorts recognized and 47% longs recognized. The misclassification rate for shorts as longs was 33%, and the misclassification rate for longs as shorts was 11%.

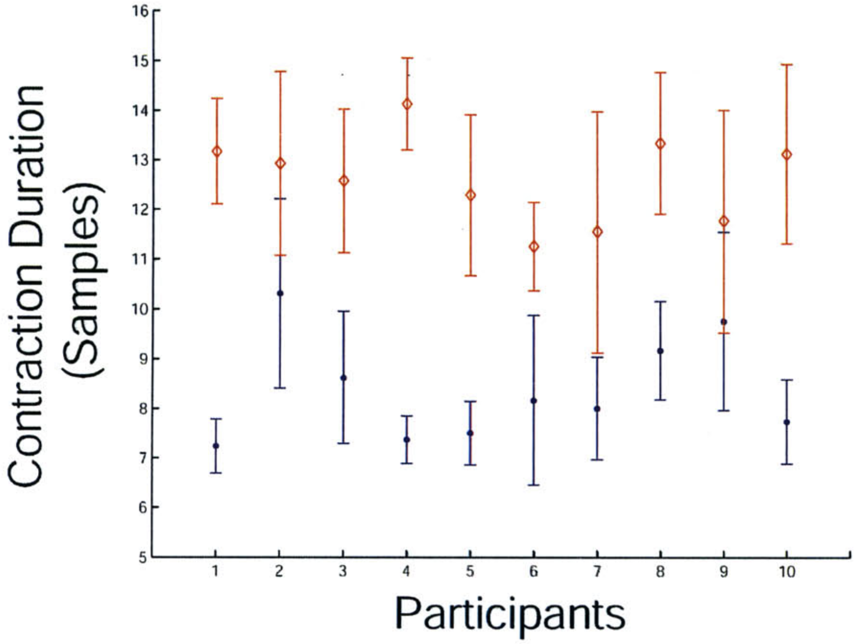


Figure 4-3: Mean and standard deviation error bars for long and short contraction durations. Closed circles indicate means for short and open circles indicate means for long.

4.1.5 Discussion

Users were able to control the system consistently with only the feedback that a contraction was recognized. The generic contractions accuracy of 96% indicates EMG can be used successfully as a controller.

The recognition of short and long contractions offline using the mixed data set was fairly low. This may have occurred because the on-line algorithm recognized a small range of contraction durations; therefore the longs may not have been sufficiently different from the shorts for the participants to accurately produce them. The range of contraction durations was set from pilot studies, which indicated most false positives occur from very long muscle contractions, therefore a trade-off between reproducibility of long and short contractions and increased false positives may occur if the range is widened.

It is important to note the durations of the short and long contractions are subjective because the participants were not given feedback to their actual durations. Therefore the participants trained themselves on what they considered were long and short contractions. If the participants were given feedback for their contraction durations, they may learn to consistently make different long and short contractions.

There were no significant differences in the subjective workload tests between contraction tasks (one-way ANOVA F4,45=0.39,p<0.82). Though not reflected in the workload score, after the experiments some participants stated they felt longs were more difficult than shorts. In addition, we noticed the three participants that required feedback in the first familiarization task became frustrated when they could not make the system recognize their contractions; however, at the end of the experiment they were comfortable using the system.

4.2 Second Study, Experiment 1: Controlling an Audio Menu with One or Two Arms

Once the first study confirmed the basic usability of EMG to recognize subtle gestures, a second study aimed at exploring a more complex scenario was performed. In this case subjects selected items from an audio menu through subtle gestures, performed with one or two arms. While the first study assessed the EMG sensor as a single bit controller, the second study examined how to express multiple bits of information, either by using two controllers at the same time on different arms, or using a single controller to select one of multiple options presented over time. Similar to the first study, the experiment evaluated the system usability in a mobile context, so subjects performed tasks while in a simulated mobile scenario, following once again the setup successfully employed by Pirhonen et al. [68].

More formally, the hypotheses for this study are:

1. EMG-based recognition of subtle gestures can be used for complex interactions with multimodal interfaces;
2. the interface bandwidth can be increased by using a single controller to select one of multiple choices presented over time;
3. EMG controllers can be used concurrently on multiple muscles to increase the interface bandwidth;
4. using multiple muscles is more efficient than using a single muscle, as there is less time pressure;

4.2.1 Experimental Design

Using the wireless EMG device, the participants performed three walking tasks, one without controlling any interface (to determine the subject's preferred walking speed), one while controlling the audio menu with one arm and one while controlling the audio menu with two arms. Each of the two menu controlling tasks was preceded by a short familiarization session. While walking, participants navigated 8 meter laps around obstacles setup in a regularly trafficked walkway at MIT Media Lab, see Figure 4-4. This setup was similar to the one used in the first study and reported by Pirhonen et al. [68].

The walking speed of subjects during each task was used as an index for the effectiveness of the interface. Petrie et al. [67] pointed out that if a mobile interface has a negative effect on users, it will be reflected in them slowing down while walking. The same measure was later used in other mobile HCI studies [68, 53]. Because subjects walked in laps of fixed length the lap completion time was measured as a proxy for walking speed. The subjects' preferred walking speed (PWS), i.e. the speed at which they walk while not using any mobile device, was measured at the beginning of the experiment as a reference for comparison.

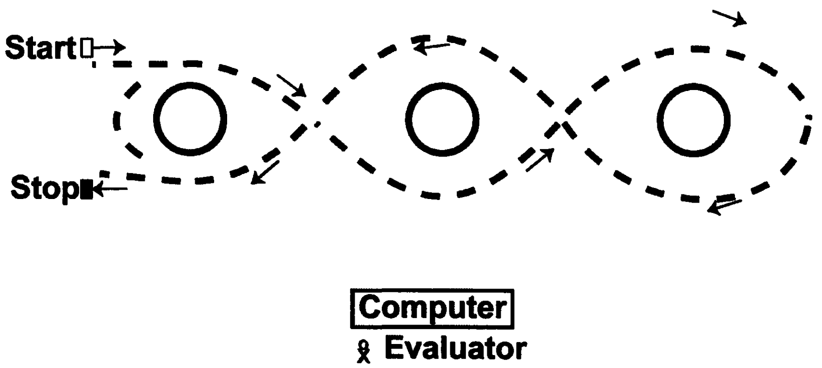


Figure 4-4: Route walked by participants in Experiment 2.

Each session started with the placement of electrodes of the same type used in the first study: disposable, sold-gel, self adhering, Ag/AgCl 9mm disc surface electromyogram electrodes. Differently from the first study, the participants skin was not abraded before electrode placement, as the improved amplifier (esp. by effect of the right leg driver feedback circuit) eliminated signal artifacts due to skin creams or lotions noticed in the first study. Like in the first experiment, the electrodes were placed around the upper arm, all at approximately the same distance from the elbow, to test the feasibility of embedding them in an armband. However, a new position was chosen to avoid the artifacts caused by pressure of the electrodes against the torso noticed for some participants of the first study. The electrodes were applied in three positions around the upper arm subject's dominant hand, such that one of the differential pair input electrodes was centred on the biceps brachii, the other differential electrode was on the outside middle of the upper arm, between the biceps and the triceps, and ground was placed on the back of the upper arm, away from the muscle of interest (see Figure 4-5). After the electrodes were applied, the wireless EMG device was mounted to the upper arm with an elastic band between the electrodes and elbow.

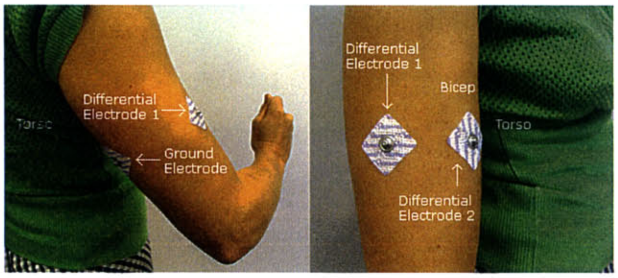


Figure 4-5: Electrode placement used in the second user study.

Participants were given written instructions that informed them that the study was assessing an EMG-based interface and they would control the system using their biceps while walking using a subtle contraction that could be performed with their arm relaxed at their side. They were also informed that the contraction recognized has a minimum and maximum duration and a minimum strength requirement. Subjects were encouraged to try to perform the contractions in a subtle way, without performing much visible movement while activating the controller, however the experimenter explicitly said that performing gestures in a subtle way is a matter of training, so if after a few attempts subjects could not easily perform the gesture in a subtle way, they were suggested to fold their arm.

During the familiarization sessions, the wireless EMG device streamed 10 bit values at 160 Hz over serial Bluetooth to a 1.7GHz Pentium4-M PC running Linux. A custom-written application, running on the PC, was used to visualize the signal and detect the gestures. The experimenter visually inspected the signal streamed from the armband device to ensure electrodes were in the correct positions. During this phase participants stood and received tactile feedback, with associated audible noise, when the system recognized a contraction. The system provided no further feedback as to the amplitude or duration of the contraction. Because the requirement for minimum training was already proved in the first study; to speed up the procedure the experimenter coached participants if they could not learn to control the system within the first two minutes of familiarization. Based on the signal recording displayed on screen and knowledge of the detection algorithm, the experimenter guided these subjects in performing longer, stronger or shorter gestures, sometimes suggesting them to push or pull on pieces of furniture. In all cases, within two minutes of training subjects were able to reliably control the device. During the familiarization, participants were also asked to attempt to perform the gesture while walking around the obstacles used for the subsequent phase of the experiment. The entire process did not exceed 15 minutes. After the familiarization phase on the arm of the dominant hand, the same procedure was repeated for the other arm. On the second arm subjects generally picked up the gesture very quickly, and the second arm familiarization lasted at most 10 minutes.

Measurement of Preferred Walking Speed

After the familiarization phase on both arms, subjects were asked to wear a pair of different armband devices (used to control the audio menu subsequently), and their preferred walking speed was recorded: subjects were asked to walk for 10 laps and the experimenter recorded the time to complete each lap.

Audio Menu

The audio menu used for the the experiment simulates what could be employed on a mobile phone. The menu contained four items, all related to different ways to handle incoming calls and they accessed sequentially from item 1 to item 4:

1. "Reject call"
2. "Ignore call"
3. "Reject call and send, 'I will call you back later.'"
4. "Reject call and send, 'In a meeting; call back if urgent.'"

As the menu was navigated the description of the current item was read, just once, by a computer voice synthesized through the AT&T Natural Voices Text-to-Speech Engine [4]. When a menu item was selected, the action was confirmed by the same voice.

Two conditions were used to access the menu:

- In the first condition, referred to as *two-arm*, subjects used the arm of the dominant hand as "next" and the other arm as "select": every time a contraction was performed with the dominant hand's arm the next item on the menu would become the *current* one; a contraction with the other arm would select the current item. The first time the next action was performed item 1 became the current item, if the same action was performed on the last item the menu "wrapped around" and item 1 became the current item.
- In the other condition, referred to as *one-arm*, the current item was automatically advanced, two seconds after the item description was read. In this way subjects could operate the interface just with one arm, used to select the current item. Subjects were asked to chose one arm to control the interface, at the beginning of the task. Similar to the first condition, the menu "wrapped around": after the last item the navigation re-started from the top.

To simulate realistic conditions of use, subjects were prompted with audio stimuli mimicking incoming calls. At randomized intervals of length uniformly distributed between 5 and 25 seconds, a synthetic voice of the same quality used for the menu items would announce an incoming call. Each time one caller would be randomly selected with uniform distribution from the following four: "Phone number 617 452 5695", "Prof. Smith", "Mom cell phone", "Alex office". Subjects were informed of the four potential callers and were instructed to react to each call following the instructions in Table 4.2.

It was generally necessary to explain to subjects that "reject call" would cause the caller to notice that his or her call was rejected, while the "ignore call" option would give the impression that the person called might not hear his or her phone ringing.

All 12 subjects participated in both tasks: within-subjects design. The *one-arm* and *two-arms* tasks were performed in a fully counterbalanced order. During the *two-arms* task, a total of 235 stimuli were presented to all subjects, corresponding to an average of 10.25

Caller	Reaction	Mnemonic Note
Phone number 617 ...	Reject the call	This is a number you do not know, so you just want to reject the call because you are busy.
Prof. Smith	Ignore the call	This is your boss, you want to ignore his call.
Your mother	Reject the call and send, "I will call you back later."	You are busy and cannot answer the call, but you send a "call you back" message not to alarm your mother.
Alex	Reject the call and send. "In a meeting, call back if urgent."	Alex might need to contact you for an emergency.

Table 4.2: Instructions and mnemonics for Experiment 2 in the second user study.

stimuli per subject (SD=1.055). For the *one-arm* task, a total of 112 stimuli were presented, corresponding to an average of 9.33 stimuli per subject (SD=0.65). To limit the overall duration of the study, the *one-arm* was stopped after two full cycles, from Item 1 to Item 4, which counted as a miss. In a similar way, the *two-arms* was disabled after 40 seconds. The tasks were performed while walking laps as described above. The walking speed was recorded and compared to the control case. Subjects heard the stimuli and the audio menu item descriptions through wireless headphones. This ensured that variations in the ambient noise of the laboratory did not have an effect on performance, and reduced the noise generated by the vibrating motor.

4.2.2 Description

Participants were 12 adults: 8 women and 4 men all volunteers were recruited through posters on the MIT campus and university mailing lists. All expressed interest to participate in the study via email, demonstrating a minimum familiarity with computer systems, and they were compensated $10 per hour. All subjects were naive in that they did not use an EMG-based interface before.

Figure 4-6: One of the participants controlling the audio menu. Audio is heard through the wireless headphones and the Intimate Communication Armbands are invisible under the T-shirt sleeves.

4.2.3 Results

Overall, subjects performed correct selections of items from the audio menu for 226 of the 235 stimuli presented, corresponding to 96.2% correct selections. Incorrect selections were performed in 6 cases (2.5%), in all except one of these an item adjacent to the correct one was selected. In 3 cases (1.3%) no selection was made. In the *two-arms* condition subjects performed correct selections for 120 of the 123 stimuli presented, corresponding to 97.6% correct performance; in the same condition 2 erroneous selections (1.6%) and only 1 missed selection (0.8%) occurred. In the *one-arm* condition subjects performed correctly for 106 of the 112 stimuli: 94.6%. The number of errors in this condition was 4 (3.6%) and 1 miss (0.9%) occourred.

Out of the 12 subjects, 7 performed perfectly in both conditions (100% correct selections), and other 2 subjects achieved a perfect score on at least one condition. Only 5 false positives were detected during the entire experiment, but these did not affect the task performance as they happened after a selection was made and before the subsequent stimulus. Additionally, two times subjects reported that an incorrect selection (included in those reported above) was made because of a false positive.

A one-way ANOVA showed no significant differences in the subject walking speed, when comparing the data corresponding to the control condition, *two-arms* condition and *one-arm* condition. Most of the subjects walked slower when operating the interfaces, however, 4 subjects walked faster in the *two-arms* than in the control condition, and 3 subjects walked faster in the *one-arm* condition than in the control condition.

It was observed that 8 of the 12 subjects learned to control the device very quickly, and that 4 naturally performed the gesture without much movement of the arm. When asked at the end of the experiment, 7 out of 10 subjects expressed a preference for the *two-arms* condition, generally because this provided more control and faster operation; only 2 out of 10 subjects preferred the *one-arm* condition and 1 did not express a preference. (note that the sample for this preference is reduced to 10, as two of the samples were unavailable)

4.2.4 Discussion

Users were able to control the audio menu consistently while mobile. The overall accuracy of 96.2% indicates that EMG can be used successfully in complex and multimodal interfaces, confirming hypothesis 1. In both conditions subjects performed with high accuracy, confirming that the interface bandwidth can be improved by either using multiple muscles or using time-multiplexing strategies with a single controller (hypotheses 2 and 3). The higher percentage of correct selections when two arms were used to control the interface, and the preference expressed by the subjects confirm that the *two-arm* modality of interaction is more efficient than the *one-arm* modality (hypothesis 4), of course with the extra expense of another controller. However, the high percentage of correct selections when only one arm was used (94.6%) suggests that time-multiplexing techniques can produce acceptable results, even more than expected.

The subjects were involved in a walking task while operating the interface and their walking speed was compared to a control condition where the subjects walked without performing any other task. As discussed above, a reduction in walking speed is generally interpreted as a sign of increased workload and need for attention on the secondary task [67, 68, 53]. Statistical analysis revealed the lack of significant differences between the two experimental conditions, and between each of the two conditions and the control. This suggests that controlling an EMG based interface, with one or two arms, does not involve a high workload or amount of attention. However, further research is required for more conclusive findings.

Most of the subjects spontaneously reported that they enjoyed taking part in the experiment and experiencing a novel and unusual way to control a computer interface.

4.3 Second Study, Experiment 2: Assessing Noticeablilty of Subtle Gestures

One of the strongest motivations for the use of EMG in the context of mobile HCI is the ability to sense isometric muscular activity, which enables the definition of input interfaces that are subtle, unobtrusive and unnoticeable by those around the users. An experiment was carried out to formally validate the hypotheses that:

1. Subtle gestures detected through EMG are not noticeable, at least when performed by a trained user;
2. The gestures are particularly inconspicuous when the device is hidden under clothing.

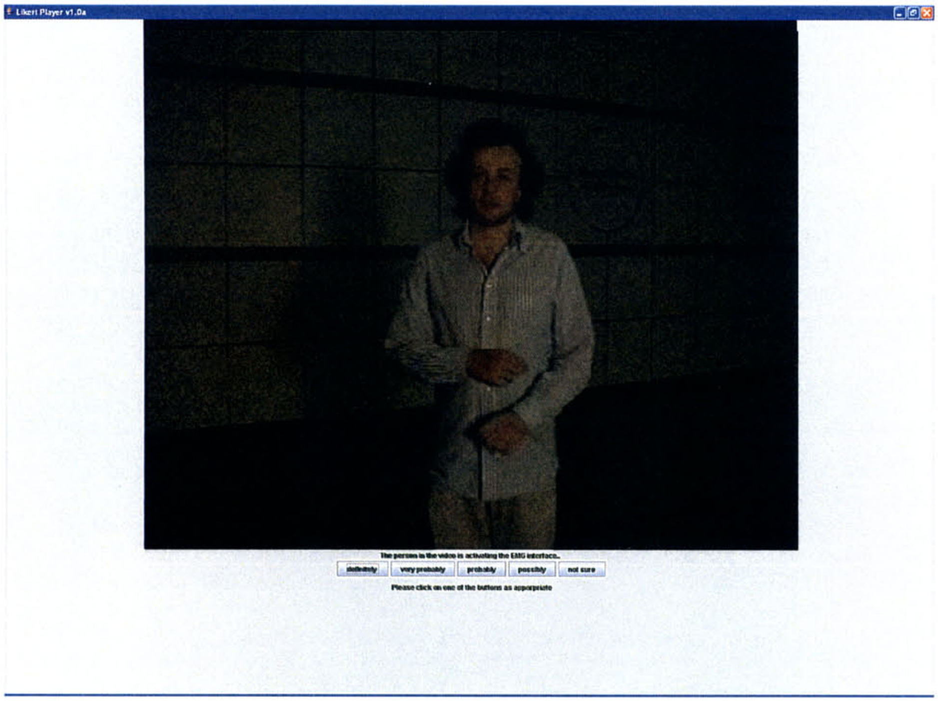
4.3.1 Experimental Design

To test the two hypotheses, subjects were asked to watch a video recording of a trained user activating the armband and to try and guess when the interface was being activated. The video showed the experimenter himself, in front of a neutral background, performing subtle gestures with his right upper arm, while talking with someone off screen, and it had no audio. The video was divided into 3 scenes, showed without interruption one after the other. In the first scene, a medium shot of duration 135 seconds, the experimenter wears long sleeves, in the second one, with the same framing and a duration of 144 seconds, with actor wearing short sleeves, while the last scene shows a close-up of the arm with the electrodes and the armband device, and lasts 41 seconds. The video was shown on a standard 17" LCD computer display, and the video window measured approximately 8" by 6" at the center of the screen, under this window 5 buttons allowed subjects to rate noticeability on a Likert scale (Figure 4-7). The same subjects who participated in the second previous experiment took part in the video rating, immediately after completing the two menu navigation tasks, so all were familiar with the EMG-based interface and the idea of subtle contractions. Subjects were informed of the purpose of the experiment and were given the following instructions:

> You will see a video (with no sound) of someone wearing the EMG-detecting armband on his right arm. The person in the video occasionally activates the EMG interface performing a subtle gesture. Below the video you will see the following sentence: "The person in the video is activating the EMG interface.."
> and five buttons labelled:
> "definitely"
> "very probably"
> "probably"
> "possibly"
> "not sure"
> Please click on one of the buttons when you think that the person in the video is activating the EMG interface.

4.3.2 Results

Guesses were considered correct if they were up to 1.5 seconds apart from the groundtruth. Overall for the long sleeves section of the video, subjects correctly guessed when a contraction was performed for only 13.9% of the attempts (19 correct guesses over 137 attempts). For the short sleeves section, 33.1% of the attempts resulted correct (47 correct guesses over



The person in the video is activating the EMG interface..

Please click on one of the buttons as apporpriate

Figure 4-7: GUI used to rate the EMG video.

142 attempts). Finally, in the close-up case 75.9% of the attempts were correct (85 over 112 attempts). The subjects' confidence on correct guesses is reported in Table 4.3, where the percentages of the correct guesses is reported for each level of confidence, so for example 36.84% in the "Long Sleeves" row and the "Definitely" column indicates that 36.8% of the correct guesses in the long sleeves case were with maximum confidence on the Likert scale. The same data is visualized in Figure 4-8.

	% overall correct	definitely	very probably	probably	possibly	not sure
Long Sleeves	13.9%	36.84%	31.58%	5.26%	21.05%	5.26%
Short Sleeves	33.1%	14.89%	21.28%	23.40%	21.28%	19.15%
Close-Up	75.9%	58.82%	25.88%	8.24%	2.35%	4.71%

Table 4.3: Results of video rating in the second user study.

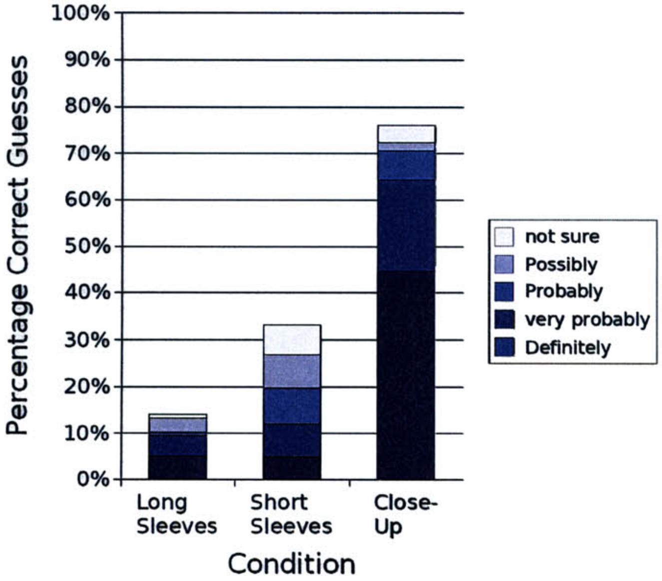


Figure 4-8: Results of video rating in the second user study.

4.3.3 Discussion

The results show that subjects cannot easily guess when the interface is activated, confirming that the interface is subtle. In the experiment subjects were told that the person in the video would at some point activate the interface, in reality this information would not be available, making the chance of noticing the interface even smaller. As expected (hypothesis 2), when the armband is hidden under clothing it becomes much less noticeable. Most of the subjects informally reported that they found it difficult to tell when a contraction was performed.

The results can be compared to the probability of a correct uninformed guess, that is the probability of correct guess assuming that subjects did not look at the video and guessed randomly. This situation can be modelled with the attempts having a uniform random distribution. Considering each of the "long sleeves" and "short sleeves" sequences separately, and remembering that an attempt is considered correct if it is within 3 seconds of a contraction, a high enough number of attempts evenly spaced in time would give 100% chance of correct guess. The minimum number of attempts for 100% chance of guessing is $N_{100\%} = D_S \ / \ D_a$, where D_S is the duration of the sequence and D_a is the uncertainty interval, in this case 3 seconds. The "long sleeves" condition lasted 135 seconds, so $N_{100\%} = 45$ attempts would give a 100% chance of guessing correctly.

During the experiment subjects cumulatively attempted to guess 137 times, corresponing to an average of 11.4 attempts per subject, and to a 11.4 / 45 = 25.3% chance of correctly guessing. In the "short sleeves" condition, 142 attempts were made corresponding to an average of 11.8 attempts per subject, over 144 seconds, so $N_{100\%} = 144 \ / \ 3 = 48$ and the uninformed guess chance is 11.8 / 48 = 24.6%.

Therefore, in the long sleeves condition the subjects guess performance, 13.9%, was much worse than completely random,25.3%, implying that watching the video did not help guessing, confirming that the contractions are unnoticeable. In the short sleeves case subjects guessed is 8.5 percentage points better than chance, however overall fairly low. The results of the close-up condition, where subjects guessed correctly most of the time confirm that participants understood the task.

4.4 General discussion

The results from the two studies demonstrate that the Intimate Communication Armbad can be reliably used in a mobile context. In both the initial and the audio menu experiments novice subjects learned to use the system very quickly, with little feedback about their performance. Subtle gestures proved to be effective in controlling a multi-modal interface even when mobile. While expressing different subtle gestures with a single arm seems not to be very reliable (at least with the current detection algorithm), subjects did not have any problems in using multiple muscles at the same time, nor to use one single muscle to select one of different options presented over time.

The gestures recognized by the armband device are indeed subtle, the results of the last experiment show that it is hard for observers to guess when someone is performing a gesture.

Part III

Notifying Glasses

Chapter 5

Background: Peripheral Vision, Displays and Notification Systems

The design of the Notifying Glasses — the second novel Intimate Interface presented in this thesis — is based on previous research about peripheral vision and peripheral displays, near-eye displays and notification systems. This chapter provides an overview of relevant findings in these fields.

5.1 Peripheral Vision

Peripheral vision is at the edge of the field of view; it is very sensitive to movement and less to detail and colour compared to central or foveal vision. In fact, the periphery of the retina is richer with rods (visual perception cells responding to movement) and has fewer cones (visual perception cells responding to colour) as compared to the center (fovea). Peripheral vision is often used unconsciously and plays an important role in orientation and navigation [87]. Even if not without criticism, research in cognitive psychology [48] suggests that peripheral vision can generally be treated as a separate (albeit not independent) channel from foveal vision.

5.1.1 Visual Field Narrowing

Peripheral vision is affected by “visual field narrowing”: studies observed that peripheral vision is temporarily reduced under conditions of high workload in the central visual field or stress [75, 89]. Early studies suggest that the nature of this narrowing is perceptual: higher workload on a task in central vision would temporarily induce “tunnel vision” [88]. More recent studies [89] confirm the narrowing, but favor a “cognitive tunnelling” interpretation, according to which the narrowing is related to attention rather than perception. Stokes, Wickens and Kite [75] report that the tunnelling might be selective: it affects the recognition of targets but not the orientation function of peripheral vision.

5.2 Peripheral Vision Displays

Early examples of peripheral displays were built and marketed in the late nineteen fifties as instrument landing aids for aircraft [75]. These displays were electro-mechanical devices designed to attract the attention of pilots while they were focused on other parts of the aircraft instrumentation. Early laboratory experiments on aircraft peripheral displays were reported in the early sixties by Brown, Holmquist and Woodhouse [9]. They compared peripheral displays with traditional instrumentation and found that the latter performed better. Later studies report performance improvement if peripheral displays are used to show redundant information for tracking tasks [75]. A more recent peripheral display for aircraft instrumentation is the Peripheral Vision Horizon Display (or “Malcolm Horizon Display”) [55], a laser projected line reproducing the horizon line. Overall human factors literature shows interest for the potential advantages offered by peripheral displays, however, their effectiveness has been often questioned (see [75] for a review). Recent studies [62] report firmer performance improvements.

5.3 Near-eye Displays

In a different application domain than aviation, Ebrahimi and Kunov proposed a wearable peripheral vision display to help lip-reading for profoundly deaf people [23]. The display is embedded in eyeglasses and connected to an audio processing system. Speech features that cannot be detected by lip-reading are visualized on the peripheral display, a 5 by 7 matrix of LEDs positioned in the side of eyeglass frames. Significant improvement of lip-reading performance for profoundly deaf patients was reported using the system.

Other near-eye displays, generally referred to as head-mounted displays (HMDs) or eyeglass displays, have been reported since the nineteen sixties. These are graphic displays worn near the eyes, generally creating the perception of a large display about one meter away from the user. HMDs and eyeglass displays have been proposed both for specific and general purpose applications [5], often with a mixed reality interface paradigm. In all cases, the display has a limited field of view and it is positioned in the users foveal vision.

5.4 Ambient Peripheral Displays

Researchers in the area of HCI and ubiquitous computing referred to periphery and peripheral displays in a more general sense, referring to the periphery of attention. In 1995 Weiser and Brown [85] introduced the concept of "calm technology" as technology that can easily move between the periphery and the center of users attention. The authors point at the art piece "Dangling String" as an early example of peripheral, calm technology. "Dangling String" is a piece of plastic wire hanging from the ceiling and connected to a motor that makes it spin according to the amount of traffic on an Ethernet network. According to the authors, users can "attune" to the movement and noise of the string, but only notice sudden changes, informing them of irregularities in the network traffic. After Weiser, a number of researchers and designers proposed a variety of peripheral interfaces, both as separate devices [16, 21] or as part of a computer's graphical user interfaces (GUIs) [12, 54].

In the first case the devices are generally referred to as ambient displays: pieces of furniture or architectural elements that change their appearance or move to display remote signals; examples are light fixtures connected to the number of accesses to a web page [21] and picture frames that display health and personal information of a remote person [16]. In the other case, information — generally text — is displayed on the border of a computer screen as part of a standard desktop graphical user interface; examples are "news tickers" [54] and applications that show notifications for incoming email messages.

Heuristics have been proposed to evaluate ambient peripheral displays in the physical environment [56] but not many user studies have been reported to date (with a notable exception [17]). More systematic evaluation has been reported for peripheral displays within GUIs. Maglio and Campbell [54] compared how three types of scrolling displays performed in terms of distraction and memorability of information displayed measuring the performance drop on a text editing primary task. They report that motion in the periphery can be profitably used to signal display update, while continuous motion has a distractive effect without increasing the memorability of the content displayed. Bartram et al. [7] studied how icons' movement on computer screens can convey information and how much it negatively affects users in terms of distraction. Motion was detected better than changes in colour and shape, especially in the periphery. Contrary to Bartram et al.'s prediction, there was no significant interaction between central workload and distraction caused by motion.

5.5 Notification Interfaces

While some of the peripheral displays tackle notification, recent research examines the notification problem in the specific context of interaction with mobile devices. Hansson et al. [33] propose a classification of mobile notification systems according to subtleness and publicity. They suggest that it is desirable for notifications from mobile devices to be not only subtle but also public so that people co-located with the user are aware of the interaction. Following these guidelines the same authors propose the "Reminder Bracelet", a prototype wristband on which LEDs blink to notify reminder cues from a PDA.

Marti and Schmandt [58] approach interruptions from a group voting perspective: each member of a (co-located) conversation group wears a finger ring that vibrates when any of the members has an incoming call, without indication of who the call is directed to. Any user can block or veto the incoming call by subtly pressing a button also embedded in the ring. Campbell and Tarasewich [13] explore the limits of minimal visual notification displays in terms of amount of information that can be displayed and user comprehension and learning. Two user studies are reported based on a desktop computer display simulating a small number of multicolour LEDs, which could be embedded in mobile or wearable devices.

An alternative approach to notifications from mobile devices is that of intelligent context aware filtering: the system combines data from environmental and body worn sensors, as well as information about incoming alerts, to determine whether and how to deliver the notification. Various prototypes [45, 39] use information from body worn accelerometers, audio, and location to infer whether a notification is acceptable either from the user's personal point of view and from the social point of view. Incoming notifications would then be blocked or delivered through a modality judged appropriate both for the user and those around them.

Vibrotactile displays provide a good solution for subtle notification. The Notifying Glasses can provide an alternative modality of notification, especially because they overcome some of the main limitations of tactile actuators (as discussed in Section 2.3): the fact that they are highly attention demanding, often audible and that they involve significant power consumption.

Chapter 6

Design and Implementation

This chapter describes the design and implementation of the Notifying Glasses, the second Intimate Interface prototype. Similar to the process follwed for the Intimate Communication Armband, the design of the glasses was performed iteratively and validated through users studies, which described in Chapter 7.

6.1 Design

The Notifying Glasses are a subtle notification display designed around ordinary eye-glass frames. The frames were augmented with a low resolution visual display: two arrays of four small red LEDs and four small green LEDs. Each array is placed at the end of the glasses' arms, near the lens, as illustrated in Figure 6-1 and Figure 6-2. The LEDs are lit at very dim intensity to display moving patterns in the wearers peripheral field of view, without disruption to those surrounding them. The position of the display allows users to easily monitor it glancing to the side without any occlusion in the foveal field of view. The patterns are displayed in low intensity to minimize irritation in case of their persistence if users decide not to react to the cue. The display was designed to utilize the *visual field narrowing phenomenon* (as described in Section 5.1); if users are under high workload the display should become unnoticeable. This makes the display naturally adaptive to users cognitive workload and stress.

Figure 6-1: The Notifying Glasses.

The glasses were designed as an accessory or *peripheral* for mobile devices. They have a Bluetooth interface so that they can be easily connected to existing mobile phones and PDAs and be used as an alternative to ringtones or vibrating alerts. Different cues can be defined through different colors or different patterns of movement. For example, different colors can be associated to different caller groups, e.g. red cues for calls from work, green cues for calls from the family, similar to what is commonly done with ringtones. By recognizing the color, users can get more information about the source of the notification in an immediate way, and make a decision about whether or not to attend to it, for example by answering the phone. By adjusting the luminous intensity and velocity of cues it is possible to influence their visibility, making them more or less noticeable. Less noticeable cues are less likely to interrupt if the user is immersed in another activity, they are more likely to be noticed later or not be noticed at all. In this way cues that are more visible can be used for notifications that have higher priority, while notifications with lower priority can be prevented from interrupting the user if he or she is immersed in another activity.

As discussed in Section 1, mobile devices are generally used in public spaces where users are surrounded by co-located people generally not involved in the interaction. In some cases users might even be engaged in person to person interaction with those around them. Therefore, alerts from mobile devices should not be a cause of embarrassment and disruption for the immediate environment. The disruptive effect of notifications should also be minimized for the addressee: while users generally want to receive notifications [33] arbitrary interruptions can have a negative effect on performance [1, 20]. In this light, it would be ideal to interrupt users only when they are not focused on other activities. Because mobile devices are carried with users for most of the day the chances of an inopportune interruption are even higher than when dealing with desktop computers. If incoming alerts can be classified by priority or importance, a notification system should map these to levels of disruption, making less important alerts result in less distracting cues.

Figure 6-2: Detail of the visual display. The LEDs are covered with a sand blasted screen to diffuse the light, not shown in this image.

These requirements must be met by designing Intimate Interfaces that present the information in a subtle non-obtrusive way and enable users to make the decision about if and how to react to incoming notifications, rather than automatically filtering notifications based on context. In general, context aware intelligent filtering could be used to determine the importance of incoming information so that this factor can be made salient to users.

To summarize, a notification system for mobile devices should:

1. deliver noticeable cues to the addressee;
2. not disrupt the users immediate environment;

3. be subtle for the addressees without distracting them in sensitive situations;
4. allow adjustable degree of disruption

Hansson, Ljungstrand and Redstrm [33] suggest that for interruptions to be more socially acceptable they should be public, so that co-located individuals can more easily understand and accept the behavior of mobile technology users. In this thesis a different approach is proposed: it should be left to the users whether and how to inform those around them, starting from the observation that a private notification can be made public, but not viceversa. It is not uncommon that mobile users want to ignore incoming notifications to continue the interaction with co-located people, in this case a public alert would only be unnecessary and distracting for the others.

6.2 Implementation

The initial prototypes for the Notifying glasses were conceived as complementary to a high resolution foveal eye-glass display. The peripheral cues would pre-alert the user about the availability of content for the foveal display, because a sudden or undesired activation of the high resolution, and high attention-drawing display could cause too much distraction and represent a danger for the user. Therefore the first version of the Notifying glasses included a single red LED glued to the side of an eye-glass display by Micro-Optical [59]. A second LED was added on the opposite side to catch the wearer's attention even if he or she was looking to either side of the glasses.

Initially, the LEDs were turned on to signal an active incoming call. It was soon realized that this was not very efficient: if the luminous intensity was too low the signal would not be noticeable, while increasing the intensity of the LED light became irritating for the eye, and moreover it caused the skin of the wearer to visibly glow and become noticeable to observers. The following step was to experiment with blinking and fading patterns on the two LEDs, which showed to be promising: cues could be noticed more reliably, while being invisible for those surrounding the wearer. Because peripheral vision is known to be especially sensitive to movement, in a subsequent prototype the number of LEDs was increased to 4 on each side, so that moving patterns could be displayed.

The current prototype includes LEDs of two different colors, red and green, four of each per side. The display is controlled through the Bluetooth RFComm profile, a protocol supported by many existing mobile devices and personal computers. The display's controller behaves essentially as a sequencer: the intensity of each LED can be individually programmed to follow a pattern.

Patterns, as well as start and stop commands, are sent to the display via Bluetooth using a syntax defined by the author. The intensity of each LED is controlled through Pulse Width Modulation (PWM) at 61Hz (to avoid the perception of flickering) and it ranges from 0 (off) to a maximum of 127 corresponding to approximately 2 mcd (at the maximum intensity each LED is driven with a 50% duty cycle, a current limiting resistor of 1K Ohm is included in the circuit to reduce power consumption and because, given the short distance between the eye and the LED, only low intensities are tolerable). Each LED luminousity pattern is characterized by two intensity values that can be selected arbitraryly, and by 4 timing parameters that determine the linear interpolation of the intensity over the pattern duration. Based on the PWM period, the time increments are by 16ms. This setup allows the display of smooth moving cues by fading in one display element while the neighboring one fades out, a technique similar to antialiasing in computer graphics.

An 8-bit Atmel ATMega88 microcontroller is used to drive the display, and a PROMI-ESD Bluetooth module provides a wireless interface[41]. The sequencing and pulse width modulation on 8 independent channels were implemented in C, as no readily available convenient hardware solution was found to drive this number of independent PWM channels. Each pair of red and green LEDs are connected to one of the microcontroller's output pins, and controlled in a time division multiplexing fashion (each pair of LEDs of different colors is connected in parallel with opposite polarities, so that by inverting the applied voltage it is possible to turn on one or the other). The microcontroller board, Bluetooth module and a single cell 3.7V, 130mAH Li-Po, are housed in a box of about 3cm x 4cm x 2cm, and suspended on the back of the glasses through flat ribbon electrical wires that connect the LEDs to the display driver. The software implementation is based on events, regulated by one of the microcontroller's built-in timers, governing the turning on and off of the LEDs. A simple round-robin scheduler was implemented to handle the recalculation of the LEDs intensity according to the current sequence while still attending to the events and to commands received through the serial link.

The total power consumption of the device is approximately 30 mW, attributable to the various components as follows: the Bluetooth module consumes on the order of 10mW if communicating for about 30% of the time (26mW when communicating, 3mW if not), the microcontroller consumes about 12 mW, and the LEDs 7 mW or less assuming that they stay on most of the time. A single cell 3.7V, 130mAH Li-Po battery is used to power the device for several hours. The sum of LEDs and microcontroller consumption is significantly less than a vibrating motor, which is at least 72mW [83], making the wearable peripheral display an attractive alternative.

To demonstrate the functionality of the glasses, driver applications were implemented both for a Linux PC and for SymbianOS-based mobile phones (both series 60 and UIQ), such as the Nokia 6600 and the Motorola A1000. The phone application listens for incoming calls, turns on the glasses when one occurs, and turns them off when the user answers the phone or if the call is sent to voicemail. A demo mode is also available in which the mobile device essentially functions as a Bluetooth remote control that can display a number of patterns on the glasses. A derived application developed for the A1000 phone was used also as a test stub for one of the usability experiments.

Chapter 7

Evaluation

To validate the design of the Notifying Glasses as an *Intimate Interface* formal usability experiments were designed and run. In short, the purpose of the study was to analyze how subjects reacted to peripheral visual cues delivered through the glasses, while they were involved in other primary tasks. The initial experiments tested notification in realistic conditions: subjects were asked to report the perception of visual cues received through the glasses while they were engaged in everyday tasks such as walking or editing text on a standard PC. The results of the study showed that the glasses are effective in delivering notification cues and that the level of visibility and disruption of the cues can be adjusted by modulating the luminous intensity and the velocity of the displayed patterns. These results encouraged further investigation about the effects of variable workload on the perception of peripheral visual cues and in particular to verify whether the cognitive narrowing phenomenon (see Section 5.1) affected the use of the glasses. A second experiment using more controlled condition showed that it is possible to design *low visibility cues* that are less noticeable under high workload. These type of cues can therefore be useful to signal non time-critical alerts, for which the cost of interruption is comparable or higher than the information value (often the case for incoming messages in everyday situations). To probe the bandwidth of the system, another experiment was designed to test the recognition of cues of different colours and different movement directions.

More formally, the hypotheses for the study were:

1. subjects can perceive the visual cues delivered through the glasses while they are involved in a primary task;
2. the noticeability of the cues can be influenced by their intensity and velocity of their patterns;
3. the cues are less noticeable if received under conditions of higher workload;
4. multiple bits of information can be delivered through the glasses, encoded with different colours and movement patterns.

It must be emphasized that the all experiments described in this chapter were designed to test the visibility of the cues, and not their effect on primary task performance, therefore none of the experiments include a control condition where the primary task is performed without interruption. The effects of notification on the primary task was assessed qualitatively verifying that subjects were not impaired from completing the primary task. Quantitative measurement of performance degradation on the primary task can be interesting, but only in comparison with the degradation caused by other notification systems. Comparing different sensory modalities of interruption, though, involves different types of interaction between the sensory channel used for the primary task and that used for the notifications (e.g. visual-visual vs. visual-auditory) therefore this type of comparison was left out of the current study and left for further investigation.

From the technical point of view, the experiments required the design and implementation of software applications to display cues through the Notifying Glasses, measure the reaction time and in some cases record audio. The software was developed in C++ in Linux. A multithreaded architecture was implemented to allow precise timing measurement and stimuli presentation.

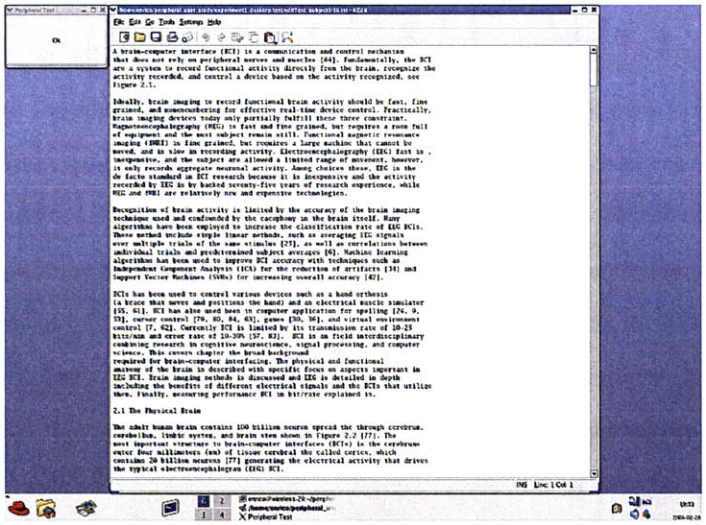
7.1 Experiment 1: Realistic Conditions

During this experiment subjects were required to react as quickly as possible to stimuli presented on the wearable peripheral display while sequentially engaged in different primary tasks. The experiment involved visual peripheral cues all of the same colour, red, but with different characteristics in terms of light intensity and velocity. Moving patterns on the display were designed as a combination of LED intensities and velocity of LED cycling: “dim” brightness 8% of the maximum LED brightness; “bright” brightness 20% of the maximum brightness; “slow” the four LEDs were lit in a cycle of period 1300 milliseconds; “fast” the LEDs’ cycle was twice as fast (period 650 milliseconds). These settings were chosen through a pilot study.

7.1.1 Experimental design

A fully counterbalanced within-groups design was used where subjects were asked to report the perception of cues from the wearable peripheral display while engaged in two primary tasks: editing text on a personal computer and walking around obstacles in a trafficked walkway of the Media Lab. The tasks were designed to ensure ecological validity for usage of mobile devices. The comparison of a stationary task and a navigation task was considered necessary given that peripheral vision plays a key role in obstacle avoidance and perception of movement [87].

The editing task was performed on a laptop computer (14” screen, external mouse) using a standard text editing application in two sessions lasting approximately 20 minutes each, interleaved by the walking task. Four different pattern types were presented during the editing task, resulting from the variation of speed and intensity: (dim, slow), (bright, slow), (dim, fast) and (bright, fast). Presentations were in balanced random order and at random intervals (uniform random distribution between 20 and 50 seconds). Subjects were asked to report perception of peripheral visual cues by clicking on a button in the computer graphical user interface, as illustrated in Figure 7-1. The text was an excerpt from a scientific dissertation [42], modified to include errors in verb conjugation and word order, in a similar manner to the study performed by Maglio and Campbell [54]. The text was selected so that editing would require longer time than the duration of the experiment.



A brain-computer interface (BCI) is a communication and control mechanism that does not rely on peripheral nerves and muscles [84]. Fundamentally, the BCI are a system to record functional activity directly from the brain, recognize the activity recorded, and control a device based on the activity recognized, see Figure 2.1.

Ideally, brain imaging to record functional brain activity should be fast, fine grained, and nonencumbering for effective real-time device control. Practically, brain imaging devices today only partially fulfill these three constraint. Magnetoencephalography (MEG) is fast and fine grained, but requires a room full of equipment and the most subject remain still. Functional magnetic resonance imaging (fMRI) is fine grained, but requires a large machine that cannot be moved, and is slow in recording activity. Electroencephalography (EEG) fast is , inexpensive, and the subject are allowed a limited range of movement, however, it only records aggregate neuronal activity. Among choices these, EEG is the de facto standard in BCI research because it is inexpensive and the activity recorded by EEG is by backed seventy-five years of research experience, while MEG and fMRI are relatively new and expensive technologies.

Recognition of brain activity is limited by the accuracy of the brain imaging technique used and confounded by the cacophony in the brain itself. Many algorithms have been employed to increase the classification rate of EEG BCIs. These method include simple linear methods, such as averaging EEG signals over multiple trials of the same stimulus [25], as well as correlations between individual trials and predetermined subject averages [6]. Machine learning algorithms has been used to improve BCI accuracy with techniques such as Independent Component Analysis (ICA) for the reduction of artifacts [34] and Support Vector Machines (SVMs) for increasing overall accuracy [42].

BCIs has been used to control various devices such as a hand orthosis (a brace that moves and positions the hand) and an electrical muscle simulator [55, 61]. BCI has also used been in computer application for spelling [24, 9, 53], cursor control [79, 80, 84, 63], games [30, 36], and virtual environment control [7, 62]. Currently BCI is limited by its transmission rate of 10-25 bits/min and error rate of 10-30% [57, 83]. BCI is an field interdisciplinary combining research in cognitive neuroscience, signal processing, and computer science. This covers chapter the broad background
required for brain-computer interfacing. The physical and functional anatomy of the brain is described with specific focus on aspects important in EEG BCI. Brain imaging methods is discussed and EEG is detailed in depth including the benefits of different electrical signals and the BCIs that utilize them. Finally, measuring performance BCI in bit/rate explained is.

2.1 The Physical Brain

The adult human brain contains 100 billion neuron spread the through cerebrum, cerebellum, limbic system, and brain stem shown in Figure 2.2 [77]. The most important structure to brain-computer interfaces (BCIs) is the cerebrum outer four millimeters (mm) of tissue cerebral the called cortex, which contains 20 billion neurons [77] generating the electrical activity that drives the typical electroencephalogram (EEG) BCI.

Figure 7-1: The GUI setup used for the part of the first experiment. The large window was used for text editing and the button in the smaller window (top-left) was used to report perception of peripheral cues.

For the walking task, participants navigated 8 meter laps around obstacles set up in a regularly trafficked walkway in Media Lab, see Figure 4-1. This setup was similar to the one reported by Pirhonen et al. [68], who noted that it allows measurement while preserving realism and ecological validity. The patterns presented during the walking task were of types (dim, slow) and (bright, slow). Presentations were balanced in random order and at random intervals. Subjects were asked to report perception of peripheral visual cues using a push-button connected to the glasses through a wire. For both tasks the cues were turned off when the subject reported seeing them or after a 30 second timeout. Reaction times were recorded automatically.

7.1.2 Description

Ten subjects were recruited from MIT (students and staff) and were compensated $10 for one hour of their time. All subjects had normal or corrected to normal vision (through contact lenses), four used contact lenses.

7.1.3 Results

Overall 94.6% of the cues were noticed within 30 seconds of their presentation. Cues of type (bright, slow) were noticed in more cases (96.5%) before the timeout, compared to other types (95% of type (bright, fast), 94% of type (dim, slow) and 93% of type (dim, fast) were noticed within 30 seconds of their presentation).

Cues of type (bright, fast) were noticed faster than the (dim, slow) type (means of 4.73 sec SD = 0.36 and 6.63 sec SD = 0.36 respectively, two-way one-factor ANOVA and Tukey-HSD $p<0.001$), both while walking and editing. The comparison of reaction times to all the four cue types in the editing task (two-way two-factor ANOVA on cue intensity and cue velocity) revealed that the bright cues were noticed significantly faster than dim cues ($p<0.001$ and Tukey-HSD $p<0.001$), while the velocity did not have a significant effect. The results are summarized in the cumulative distribution curves shown in Figure 7-2 and Figure 7-3. These curves show the fraction of total number of presentations that were perceived within a given time period; for example, in Figure 7-2, about 97% of all patterns of type (bright, slow) were seen within 10 seconds, while only about 79% of those of type (dim, slow) were detected by the same time.

7.1.4 Discussion

The results of experiment 1 confirm that the wearable peripheral display can be used to deliver noticeable cues while users are engaged in everyday activities, even when mobile, confirming the first hypothesis. Figures 7-2 and 7-3 show that 94% of the most visible cues were always noticed within 15 seconds of their presentation. The gradual response in reaction time confirms that the display is subtle in delivering cues. The distribution curves associated with patterns of different brightness and speed confirm that it is possible to adjust the level of disruption of the cues making them more or less noticeable, validating the second hypothesis.

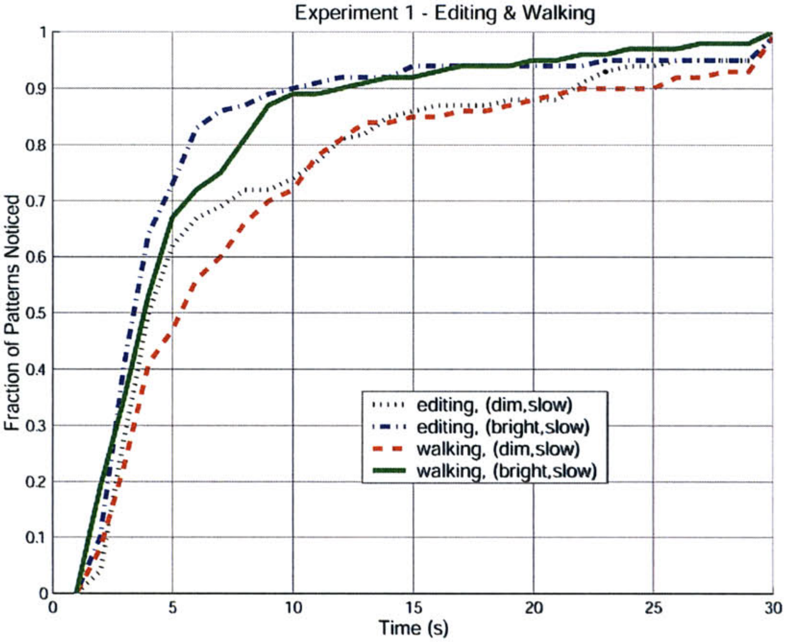


Figure 7-2: Cumulative distribution curves for (dim, slow) and (bright, slow) patterns in experiment 1. The data is relative to both the "Walking" and "Editing" tasks, as indicated in the legend.

A number of subjects (six) spontaneously reported to periodically "check" for incoming alerts, deliberately shifting their attention between the main task and looking for notifications. This behavior is similar to what Weiser [85] argued for calm technology: that it can the be easily shifted between periphery and the center of attention. The shift is possible thanks to the selectivity of foveal vision, while it would not be possible with audio or vibrotactile alerts, which tend to instantaneously capture the users attention [28] (discussed in [69]).

7.2 Experiment 2: Variable Workload

The second experiment was designed to measure the effects of primary task workload on the perception of the cues. To induce a different workload subjects were asked to read a narrative text from a computer monitor at two different speeds. Each reading task lasted

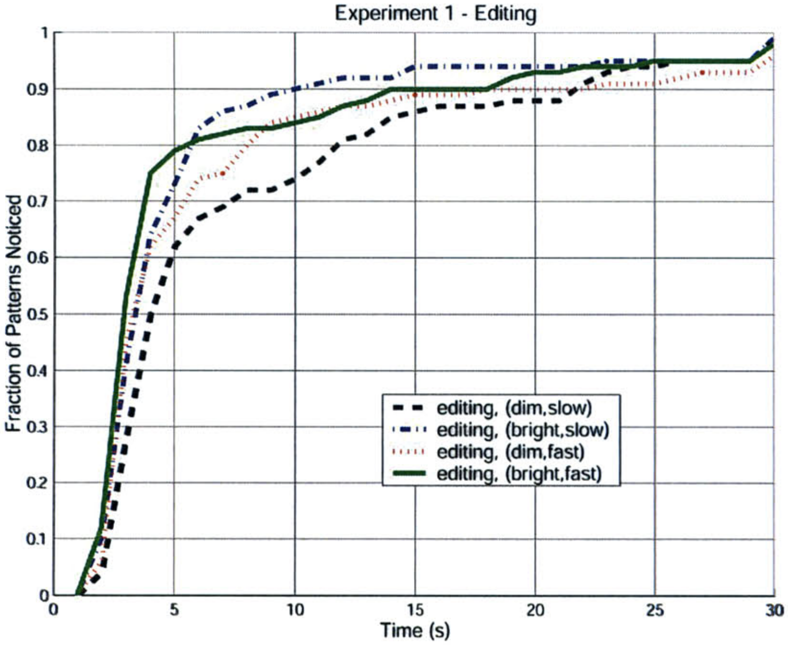


Figure 7-3: Cumulative distribution curves for the editing task in experiment 1.

approximately 10 minutes and was repeated twice (same speed, same text), for a total of 4 conditions ({high speed, low speed} x {first time reading, repeated reading}). Subjects were instructed to keep one of their hands on the computer's keyboard and press it as soon as a peripheral cue was noticed.

7.2.1 Experimental Design

The experiment used repeated measures, within-subjects design, counterbalanced by unique task and pattern. Patterns of types (dim, slow) and (bright, fast), all of the same color, red, were presented during each of the sessions in balanced random order presentations at random intervals uniformly distributed between 25 and 70 seconds. Cues were kept on for a maximum of 15 seconds, if the timeout was reached the system passed to the next presentation.

The text was the beginning of a short story [61] and it was displayed on a standard 19" LCD computer monitor using 14 point font. A software application was written in Java to show the text two lines at a time and advance the content one line at a time automatically, a setup commonly used for reading speed experiments [14]. At the beginning of the experiment, using a different text [81], subjects were asked to adjust the display rate to be as fast as possible while still allowing them to read and understand it. The resulting speed was then used as "high speed" while half of the value was used as "low speed". Each subject was then presented the text starting from the beginning at either high or slow speed, for approximately 10 minutes. After the first presentation was repeated, the continuation of the text (allowing 2 lines overlap) was displayed at the alternative speed. To ensure that subjects actually engaged in reading, they were given 5 questions about the content before the beginning of calibration, and were asked to answer them at the end of the experiment.

7.2.2 Description

Ten new subjects were recruited from the MIT population (students and staff) and were compensated $10 for one hour of their time. All subjects had normal vision.

7.2.3 Results

Overall 94% of the cues were noticed within 15 seconds from their presentation. All of the highly visible (bright, slow) cues were noticed before the timeout regardless of the primary task. The less visible (dim, slow) cues where noticed 80% of the times while users were engaged in the first time reading at high speed, the perception rises to 88% during repeated reading at high speed and first time reading at low speed, and to 96% during the repeated reading at low speed.

The notification cues were noticed faster when the users read at low speed than at high speed (means of 0.99 sec SD=0.09 and 1.37 sec SD=0.09 respectively, two-way three-factor ANOVA $p<0.01$, with factors cue type, reading speed, reading repetition, Tukey-HSD $p<0.01$). Different cue types also caused significant differences in reaction times. Subjects detected (bright, fast) cues quicker than (dim, slow) cues (means of 1.02 sec SD =

0.09 and 1.34 sec SD = 0.09 respectively, $p<0.05$). Figure 7-4 shows the comparison of reaction times marginal means for all the tasks and patterns used in the experiment, with 95% confidence level intervals (Tukey-HSD). All subjects were able to correctly answer the questions about the text content.

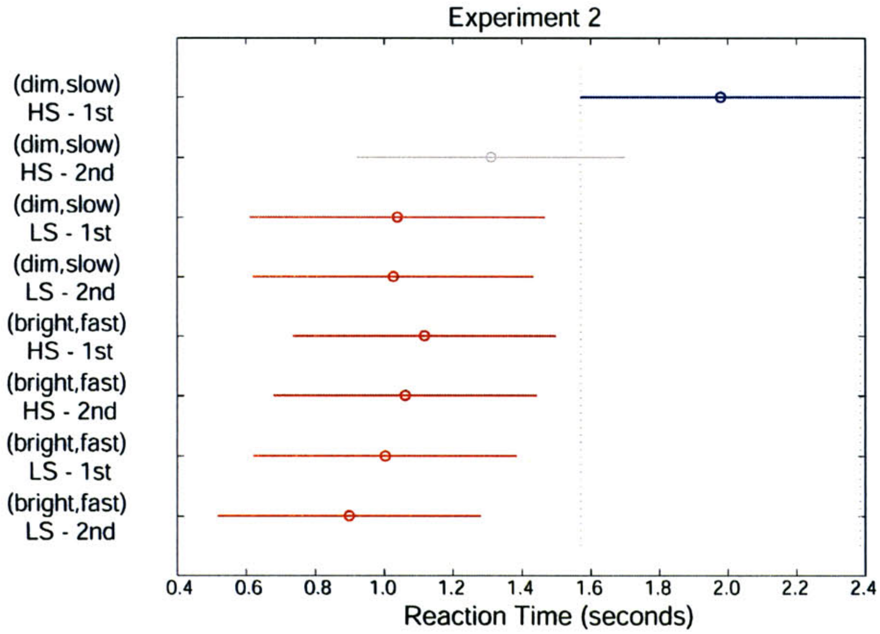


Figure 7-4: Comparison of mean reaction times for all the tasks and patterns of experiment 2, with 95% confidence bars.

7.2.4 Discussion

The results of this experiment confirm the third hypothesis: the visibility of the peripheral cues depends on the workload of the primary task. The data also reinforces the second hypothesis: the level of disruption and visibility of cues can be controlled through their brightness and velocity.

Figure 7-4 shows that different tasks cause significant differences to the perception of low visible (dim, slow) cues, while the effect on the more visible (bright, fast) cues is not as strong. Thinking of the primary task workload as a barrier for the perception of peripheral cues, this data suggests that the disruption level of different cues determines how high of a workload barrier the cue can cross.

7.3 Experiment 3: Recognition of Multi-Colour Cues

The third experiment was designed to investigate the perception of cues characterized by different colours and different moving patterns in relation to variation of primary task workload. Similarly to the previous experiment, different workload was induced through variable reading speed and repeated reading of the same text. However, because the results from the previous experiment revealed that only "reading for the first time at full speed" and "reading for the second time at half speed" produced significant differences in the reaction time, only these two conditions were tested. Six different types of cues were used in this experiment resulting from the combination of 3 different colours, red, green, red+green, with 2 different moving patterns: front-to-back and back-to-front. Differently from the previous experiments, intensity and velocity of the patterns were kept constant. At the beginning of each session, subjects were shown the 6 different patterns and were asked to identify them and chose a name to identify each pattern. Subjects were asked to react to the perception of each pattern by pressing the computer spacebar and pronouncing aloud the name that they had chosen for the pattern shown. The same computer used to display the text and drive the glasses was used to record audio immediately after each cue was presented. The cue identification audio clips were analyzed off-line manually.

7.3.1 Experimental Design

The experiment used repeated measures, within-subjects design. Patterns of the 6 types described above were presented during each of the sessions in balanced random order presentations at random intervals uniformly distributed between 10 and 40 seconds. Cues were on for a maximum of 15 seconds, if the timeout was reached the system passed to the next presentation.

The text was the beginning of a short story [60] and it was displayed on a standard 19" LCD computer monitor using 14 point font. The same Java application developed for the previous experiment was used to display text two lines at the time with constant display speed. The same procedure described for the second experiment was follwed to determine the full reading speed: using a different text [61] subjects were asked to adjust the display rate to be as fast as possible while still allowing them to read and understand. The resulting speed was then used as high speed while half of the value was used as low speed. Each subject was then presented the text starting from the beginning at high speed, for approximately 20 minutes. The same text was then presented at half speed. To ensure that subjects actually engaged in reading, they were given 5 questions about the content before the beginning of calibration, and were asked to answer them at the end of the experiment. During both the reading tasks, cues were presented through the glasses and subjects were requested to report their perception by pressing the space bar and identify them verbally.

7.3.2 Description

Ten new subjects were recruited from the MIT population (students and staff) and were compensated $10 for one hour of their time. All subjects had normal vision or corrected normal vision.

7.3.3 Results

The color of the cues was successfully recognized for 97.4% of the cues, the direction for 93.3%, and the two characteristics were correctly recognized at the same time for 91.3% of the cues. Only one of the cues was missed during the entire experiment. The confusion matrices for color and direction of the cues are reported in Table 7.1 and Table 7.2. One of the subjects identified all the cues correctly, while other 3 subjects correctly identified all the colors.

In the "high speed" condition the color was recognized in 97.9% of the cases, direction in 92.8%; 91.1% of the cues were correctly identified in color and direction. In the "slow speed" condition color was correctly identified for 96.9% of the cues, direction for 93.9% of them, and both characteristics were symultaneously identified in 91.4% of the cases.

A 3-way ANOVA test revealed that the colour or direction of the cues does not influence the reaction time, however, differences produced by the two different reading conditions have statistical significance ($p<0.05$). The results are summarized in Figure 7-5

	recognized as red	recognized as green	recognized as mixed
red cues	99.7%	0	0.3%
green cues	0.6%	97.4%	1.7%
mixed cues	0	4.9%	95.1%

Table 7.1: Confusion matrix for the color of the cues in Experiment 3. Note that the rows do not always add to 100 because of the one cue that was missed.

	recognized as fwd	recognized as bwd
fwd cues	95.9%	4.1%
bwd cues	9.0%	90.8%

Table 7.2: Confusion matrix for the direction of the cues in Experiment 3. Note that the rows do not always add to 100 because of the one cue that was missed.

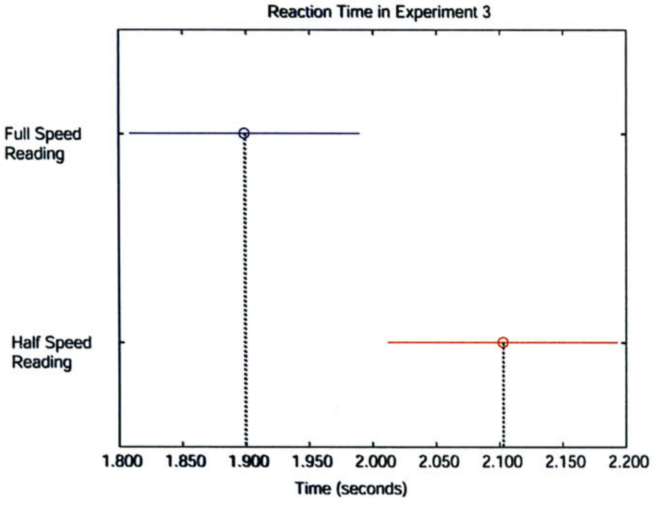


Figure 7-5: Comparison of mean reaction times for the two reading tasks of experiment 3, with 95% confidence bars.

7.3.4 Discussion

The high recognition rate demonstrates that the Notifying Glasses can be successfully used to deliver multiple bits of information through subtle visual cues while users are engaged in an another task. Critical information should be encoded in the cues color, as this feature was better identified by subjects. In particular the confusion matrix for the color of the cues shows that red is confused the least, followed by green. The use of both the colors at the same time was not as successful, but still more accurately identified than direction of movement. The cues direction was identified less reliably, even though correct recognition rate of 93.3% suggests that this characteristic can still be used to encode less critical information. Even though lower than the color recognition rate, the direction recogntion rate compares very well to the maximum recognition rate obtained through tactile displays [11].

The perception of direction of movement seems to be highly dependent on the position of the display on the user's face. At least two of the LEDs on each side of the glasses need to be in the peripheral visual field of the user, for him or her to distinguish the direction of movement. If this is not the case, because of the way the glasses sit on the user's face, it will be necessary to glance at the side to identifiy the movement.

Contrary to expectations, when reading at half speed users reacted to the cues more slowly and the overall recognition rate was lower. Probably these effects are due to the not counterbalanced experimental design: all subjects read at full speed first and then at half speed. This might have caused subjects to be more tired when reading at half speed or an habituation effect to the presentation of cues. Further experiments with a fully counterbalanced design need to be run to clarify this issue.

Part IV

Concluding Remarks

Chapter 8

Conclusion and Future Work

This thesis introduced *Intimate Interfaces*: novel interfaces that allow discrete and subtle interaction with mobile devices, in order to enable users to access the benefits offered by these devices without causing disruption to people around them.

Mobile devices allow personal and private communication from virtually anywhere and anytime, however, they are often used in a public and social context, where users are surrounded by others not involved in the interaction. Therefore, mobile users find themselves in *simultaneous realities*: the one, often public, where they are physically present and the other one, often private, created by the remote communication. The coexistence of these public and private conditions is often not easy. Currently the only solution is to suppress one of the two, for example by turning off the mobile device or by ignoring the physical reality and being disrespectful of co-located people. Intimate Interfaces are designed to soften this contrast by allowing users to put mobile devices in the background, but still within reach. The interfaces require low attention, can be used while involved in other activities, and are easy to ignore.

The concept of Intimate Interfaces was explored through the design, implementation and evaluation of two wearable interface devices: the *Intimate Communication Armband* and the *Notifying Glasses*. Both devices are novel and based on essentially unexplored areas of investigation. They have wireless Bluetooth interfaces that allow them to be easily connected to existing mobile devices and personal computers.

The Intimate Communication Armband uses electromyographic sensing to detect *subtle motionless gestures*: explicit muscle contractions resulting in little or no movement. The electromyographic sensor designed for the armband was evaluated through user studies. Experimental results show that the gestures are reliably recognized without training, neither for the recognition algorithm nor for users. Subjects were able to reliably control an audio interface using one or two arms, without problems, while engaged in a walking task. An experiment designed to evaluate the subtlety of the interface revealed that it is very difficult for observers to guess when a trained user is performing subtle gestures. The armband device also includes a tactile display, based on a vibrating motor, and can be made invisible by being worn under clothes.

The Notifying Glasses take advantage of the characteristics of peripheral vision to deliver subtle notification cues to the wearers, while being unnoticeable to those around them. To validate the design of the glasses experiments where subjects were asked to report perception of the cues while sequentially engaged in other activities were run. The results revealed that the cues do not suddenly grab wearers' attention while still being generally visible; moreover, they can be designed to meet specific levels of visibility and disruption, so that some of them are noticeable only when the user is not under high workload, as highly desirable in many practical circumstances. Subjects were able to reliably identify cues characterized by different colors and different movement patterns, while engaged in another task.

The design of interfaces and interaction techniques for mobile devices should take into account social acceptance and allow devices to be active but not disruptive. The construction and evaluation of the two prototypes proposed in this thesis demonstrates that it is possible to realize usable mobile interfaces that are intimate and subtle, and therefore socially acceptable.

8.1 Further Work

The work presented in this thesis is only probing a design space that should be explored further, investigating the cognitive aspects related to Intimate Interfaces and developing a model for *minimal interaction* with mobile devices: interaction through low-bandwidth and low-attention interfaces that allow users to get just enough information to decide whether or not to interrupt their current principal involvement and devote their full attention to the mobile device. Such minimal interaction should allow a comfortable shift of technology between the periphery and center of attention.

Future work should explore the design of more Intimate Interfaces. Auditory displays, tactile actuators, gaze tracking, touch and light sensors, to name just a few, can all serve as starting points to create new subtle input and output devices. The Intimate Communication Armband and the Notifying glasses should be integrated within specific mobile applications, to provide for example subtle remote awareness. Higher level evaluation on these applications should analyze how users adopt Intimate Interfaces for day to day use.

Further development should take advantage of the state of the art in hardware miniaturization to reduce the size and weight of both devices. Future iterations of the prototypes should take into account industrial design principles for better integration of form and function. Issues specific to the individual devices are exposed in the following subsections.

8.1.1 Intimate Communication Armband

Further investigation should explore the use of more advanced analysis techniques for the detection of subtle gestures, such as autoregressive modelling, which has been reported to be successful in some EMG literature [37]. To improve the comfort of the device, dry electrodes or electrodes embedded in fabric [66] should be included in the armband design.

The potentiality of localized tactile cues should be explored. Tactile stimuli on different parts of the body can convey a large amount of information. Armbands should be paired, so that one vibrates when the other recognizes a subtle gesture, to form a simple intimate communication system for remote awareness.

8.1.2 Notifying Glasses

Future prototypes of the glasses should allow the display of more colors, and include a bi-dimensional display, to allow the visualization of moving patterns in multiple directions. A light sensor can be employed to adjust the luminosity of the cues depending on the brightness of the environment. Integration of input devices, such as push buttons, capacitive sliders and touch sensors in the glasses' frames should the explored, to make the device a full input/output system.

Future studies should analyze prolonged use of the glasses (through day-long or week-long experiments), measure degradation of performance on primary task, comparing the effects of peripheral visual cues with other modalities, such as audio or tactile cues. Issues related to specific applications, such as spatial navigation, email or phone call alerts should also be investigated.

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