ComTouch: A Vibrotactile Mobile Communication Device

by

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Submitted to the Program in Media arts and Sciences,
School of Architecture and Planning,
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Media Arts and Sciences
at the
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Abstract

This thesis presents ComTouch, a new device for enhancing interpersonal communication over distance through use of touch. The ComTouch approach investigates how the sense of touch can be remotely represented by means of a *vibrotactile*, or touch-and-vibration, interface. Touch has potential to improve existing remote communication by allowing tactile cues to augment the audio-visual information in real-time.

The approach of ComTouch is to use this vibrotactile mapping for conveying the pressure exerted by each finger of the transmitter as patterns of vibration against the corresponding finger of the receiver. The implementation is a hand-held device that allows a user to transmit and receive patterns of vibration to and from a remote user. A pair of prototypes was built to allow exploration of remote communication using this vibrotactile mapping.

The hypothesis is that the vibrotactile mapping can be used in remote communication of *tactile gestures*, or expressive uses of touch. User studies will be performed to gauge the information content of the signals transmitted and received using the vibrotactile device in remote communication. A report of the observed usages of the vibrotactile channel will be given. This research will allow us to identify patterns of tactile communication that may inform the design of new tactile communication devices, languages and methods.

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1 introduction

*"Communication face-to-face is rich in social cues: we can see one another; we know the distance between us; and we may even be able to **touch**. Over the telephone, in contrast, there is little except the voice…" (p.38, Rutter)*

Real-time remote communication allows people to connect to each other in real-time while being physically separated. The ability to instantaneously exchange sound and text over great distances has become almost commonplace. However, commercial communication devices do not ordinarily convey a sense of touch. With rare exceptions, communicating using touch is only possible when people are face-to-face. Figure 1-1 shows the communication design space we are concerned with.

Figure 1-1. Real-time interpersonal communication methods.
Our specific design space for this project concerns remote communication, which will be broken down further in Chapter 3.

REAL-TIME Interpersonal Communication Methods for Different Places	
Remote locations	**Local**
Chat **telephone** **email** **instant messaging** **Morse code**	**Face-to-face** **Gestures** **Senses-- audio, vision, smell, taste, touch**

Touch has much meaning and information in interpersonal communication. Touch acts as an extension of the physical body. Hand shakes between business partners to signify agreement and commitment, the supportive squeeze of your hand by a friend, or even a quick tap of interruption from a stranger conveys a wealth of contextual information that is rarely present in real-time remote interpersonal communication. The promise of "reaching out to touch someone" suggests that touch is a powerful and meaningful part of interpersonal communication.

1.1 Problem Description

What is the meaning of touch in remote communication? Imagine if you really were able to reach out and touch someone in a remote place, and imagine if they could touch you in response. What is the socially shared signaling system, or *code*? What set of shared behaviors are possible? The answers to these questions on communication are directly related to the interface. With something as physical as the sense of touch, it follows that the form defines the function. The interface will determine the nature of the communication.

The goal of this research is to design and implement a sensory augmentation tool that communicates the sense of touch. A necessary step toward this goal is to explore the possible effects of a tactile channel to verbal communication. The hypothesis is that tactile information enhances audio remote interactions, and that if tactile feedback is made available, there may exist a correlation between the way tactile and audio communication channels are used. An additional hypothesis is that tactile information can enhance remote interaction, in a manner independent of the audio channel.

1.2 A Vibrotactile Mapping

Tactile touch as a modality for communication has recently begun to attract interest from researchers in the field of commercial communication devices. Modern technological advances in communication devices (such as reduced battery size, better data compression, and increased bandwidth for graphics and text) to enable new modalities for mobile real-time remote communication. What limitations exist, then, for creating a commercial touch communication device? Previous approaches have focused on accurately representing the mechanics of touch.

To create artificial haptic stimuli has been the main problem with embedding communication devices with tactile actuators. The most common method to solve this problem is to use motors. However, motors require sophisticated motion control algorithms, power storage and dissipation schemes, and quick response to generate compelling tactile effects. Motors are also too bulky for continuous use -- imagine lifting and holding a motor all the time. The use of motors also raises issues of robustness from timely wear-and-tear and being dropped. There are also safety issues as motors might exert too much force or spin too quickly for the comfort. In short, a new actuation technique is desired.

We present the use of vibration as an alternative solution to generate tactile output for communication. This dissertation investigates the potential of vibrotactile interfaces for remote communication. We describe our methodology, design, and evaluation of a new tactile communication interface.

1.3 Outline of this document

This paper describes a particular design approach to creating a tactile communication device. The design process, research background, and key design issues are identified.

Chapter 2 describes the background and motivation of this thesis, as well as related work on touch, perception and communication. Chapter 3 describes the design and prototype implementation of the ComTouch system. An implementation of a new vibrotactile mapping is proposed. A touch communication device using this mapping is presented. Chapter 4 describes initial experiments on the usage of the device in conjunction with an audio channel present interesting results. The discussion reflects on user reactions and the data are presented. The new mapping reveals three new uses, called *tactile gestures*, for the tactile information in audio conversations. Users are also able to develop their own encoding schemes, with some similarities, using the device. Chapter 5 reflects on the implications of the discovery of tactile gestures on the development of a touch language. Chapter 6 summarizes conclusions on tactile gestures from this research, and discusses future design possibilities for this research.

2 related research

2.1 Background and Motivation

In the beginning, we were motivated to build a tactile communication device. We quickly found relevant information in three main areas: the interpersonal communication work done in the Human-Computer Interfaces (HCI) field, the work on vibrotactile mechanisms in psychophysiology, and work on information transmission of tactile languages used by deaf-blind people. What follows is an overview of some terminology to familiarize the reader with the relevant research.

2.1.1. Definitions and Terminology of Touch

Haptics is defined as anything pertaining to the sense of touch. Haptic sensations can be subdivided further into two types: *passive* and *active* sensations.

The first types of sensations, tactile or cutaneous sensations, are passive and refer to the sensations applied to the skin. These sensations are based on the stimulation of receptors in the skin. Goldstein further subdivides tactile sensations into three types: *tactile perceptions* are caused by the mechanical displacement of the skin, *temperature perceptions* caused by heating or cooling of skin and *pain perception* caused by stimuli that are potentially damaging to skin. The research here is primarily concerned with the use of these tactile sensations.

The active types of sensation are *proprioceptive* and *kinesthetic* sensations. Proprioceptive sensation refers to the awareness of position of your limbs. Kinesthetic sensation refers to the sense of movement of the limbs.

From these sensations, the skin provides useful information to the brain. The combination of sensations that results in communication of information is of particular interest. In order to realize the possibilities of how to present information via our tactile senses, it is useful to know about the mechanics of touch.

2.1.2. A Brief Overview of the Mechanics of Touch

The composition of skin determines the sense of touch using the three different types of sensation described earlier. These sensations allow the skin to act in two main capacities: to separate our insides from the environment and also to provide us with information about the environment. Some of the functions of skin are to warn of danger, prevent body fluids from escaping, protect our internal organs from external irritants, exert pressure on objects, and sense temperature.

As depicted in Figure 2-1, the skin consists of many layers. The outermost layer is called the epidermis, composed of several layers of dead skin cells. Under the epidermis is the dermis, an inner layer containing nerve endings. The skin contains a vast amount of receptors throughout the epidermis and dermis.

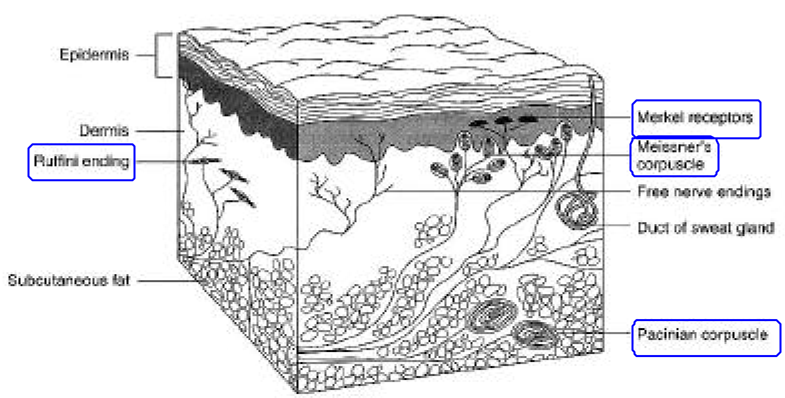
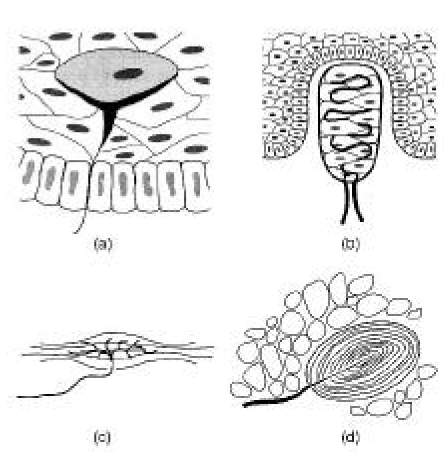


Figure 2-1. Cross section of the layers of hairless skin showing some of the receptors. The four main receptors of touch are circled. (Adapted from *Sensation and Perception* Goldstein p.438)

Figure 2-2 depicts the four major receptors for tactile perception in order of closeness to the epidermis: Merkel receptor, Meissner corpuscle, Ruffini cylinder and Pacinian corpuscle. These receptors are designed to perceive different cutaneous perceptions such as pressure, flutter, buzzing, and vibration.

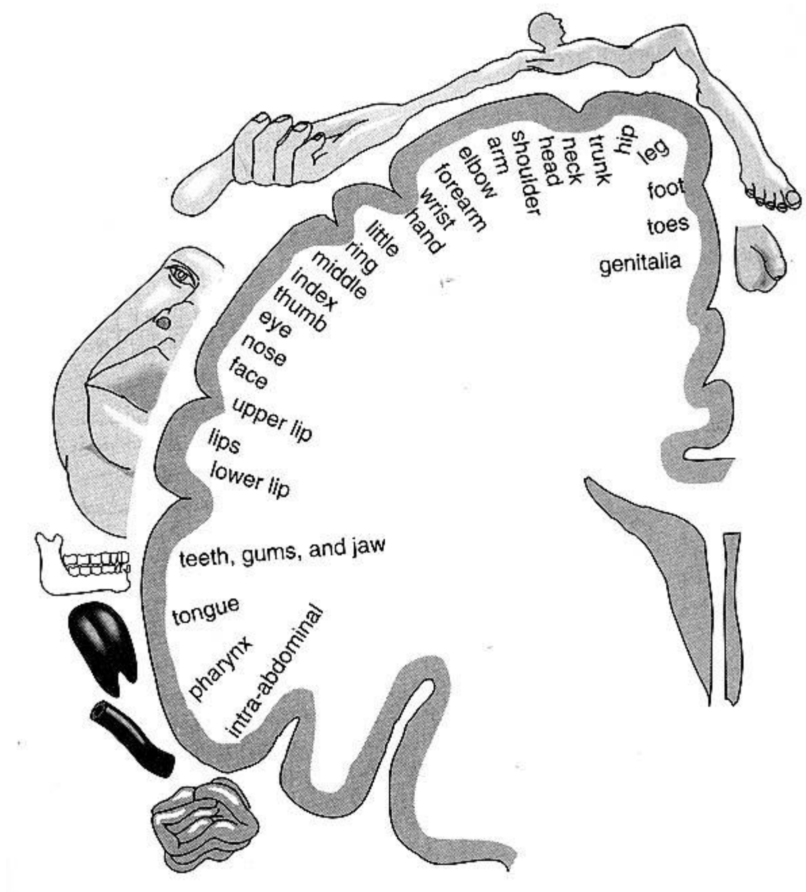
Figure 2-2. Cell receptors The four major receptors for tactile reception and their frequency range of response (Adapted from Goldstein pp.438-439.



Receptors	Frequency range	Perception
a) Merkel receptors	0.3-3Hz (slow pushin g)	Pressure
b) Meissner corpuscle	3-40 Hz	Flutter
c) Ruffini cylinder	15-400 Hz	Stretching
d) Pacinian corpuscle	10-500 Hz (very rapid vibration)	Vibration

Unlike our eyes and ears, the haptic stimuli receptors are not encapsulated in a single organ, but rather distributed along the body. A higher concentration of receptors in certain parts of the body such as hands and lips results in greater sensitivity to tactile sensations in these areas. Figure 2-3 shows the sensory homunculus diagram representing the brain's processing of the distribution of touch. Notice that the area of the hand occupies the largest cortical area. This unequal distribution shows that the brain dedicates a large area of receptors for the fingers. Compared to other body parts, our hands have a high density of tactile receptors. This makes the hand an ideal site for receiving information (Reed 1991).

Figure 2-3.The sensory homunculus diagram representing the brain's processing of the distribution of touch. Survival, perception, cognition are functions of touch in everyday life. In order to survive, we need to move --(From *Sensation and Perception* Goldstein p.449).



2.1.3. Psychological Aspects of Touch

Survival, cognition, emotion and perception are functions of touch in everyday life. In order to survive, we need to move. We need to feel around us (perception) and get these signals to our brain in order to decide where to move (cognition).

Klatzky and Lederman proved that the haptic system is very efficient at recognizing 3D objects. In their 1987 study, users optimized their tactile senses using a large number of exploratory procedures (EPs) for taking in information and manipulating objects. Some EPs are: enclosing objects with the hands, following contours, applying pressure, and using lateral motion. The researchers found that people tended to use the same types of EPs depending on the desired information needed about the object.

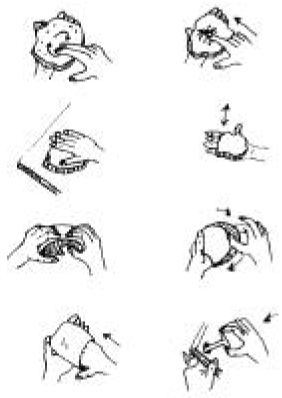


Figure 2-4. Typical movement patterns for EPs described by Klatzky and Lederman. From top left counter clock wise: lateral motion, static contact, enclosure, function test, part motion test, contour following, unsupported holding and pressure. –from p.346 (Klatzky 1993)

Figure 2-4 shows some typical EPs that are used for object recognition.

Touch does more than just give us information about our surroundings, it also helps us express emotions (e.g. patting, squeezing, stroking). Touch has high emotional value. Ackerman (p.71) writes, "We call our emotions *feelings,* and we care most deeply when something 'touches' us."

The intensity of emotion has correlations with the intensity of physical expression. The skin is the site at which the body releases endorphins for pain and excitement. Social and behavioral scientists have long used the skin conductivity as an indicator of emotion (Dawson 1990).

2.1.4. Cognitive aspects of touch in combination with other modalities

Our senses often act in unison to present a cohesive story to our mind. Crossmodal interactions are when a combination of the senses of touch, taste, smell, hearing, and vision jointly act. When crossmodal interactions occur to verify one another, cognition happens more robustly than when only one sense is acting alone. When the senses disagree, we often experience what are called *sensory illusions*, because the mind has difficulty resolving the meaning of the stimuli. One such illusion is *visual capture* or the *ventriloquism effect*, which often occurs in movies where a character's voice is perceived as coming from their mouth even though it is really coming out of a loud speaker somewhere else (Stein 1993, Goldstein 2002).

Our reliance on different senses can vary depending on the situation. For example, in the dark, our sense of sight tries to adjust to lower levels of light. Meanwhile, as one ages, the sense of hearing and sight tend to degrade.

In this research, we are particularly interested in the effect of the combination of senses. People naturally use a combination of modalities in order to understand their environment. These combinations affect perception in different ways. Three types of sensory interactions are widely studied because of their powerful effects on human perception and cognition: *sensory substitution, sensory redundancy,* and *synesthesia*.

Sensory substitution is the process of substituting information from one sensory modality for another in order to perceive an object. One example of sensory substitution is when people who are deaf rely on the lip reading, a visual sense.

Sensory redundancy *or sensory augmentation* is the process of adding information from one modality to help another. When the senses act together to verify each other, perception occurs much strongly. An example of sensory redundancy is when you see a rose, but you have to smell and touch it to verify whether it is real.

Although a rare condition, s*ynesthesia* is when stimulation of one modality triggers stimulation of a different modality. For example, a person might associate seeing different colors when hearing certain sounds. Usually, this results in a very compelling experience for the person.

2.1.5. Tactile illusions

Brown and Stevens give an overview of two ways of stimulating the skin using artificial stimuli (1992). *Vibrotactile* means to use vibration signals delivered by one or more vibrators on the skin. *Electrotactile* means to use electrical stimulation (e.g. by means of surface electrodes) to deliver signals to the skin. It is interesting to note that certain tactile stimulation can cause illusions on the skin.

One interesting phenomenon we hope to exploit is the *cutaneous rabbit*, also known as sensory *saltation* (Geldard 1972). When given a number of distinct vibrational pulses along the forearm, people felt the vibrations were moving up their arm linearly. In effect, their mind was interpolating the effect of phantom vibrators. The components necessary for this effect to occur are actuators at the desired end-points of the linear gesture, and the correct relationships in timing and amplitude between the pulses used to generate the illusion. The saltation effect has analogies in vision and audition, where the person perceives more stimuli than are actually available (Tan 2000). In Tan's study, people who were naïve to vibrotactile stimuli could readily distinguish patterns of movement without any training.

There are two significant implications of sensory saltation. One implication is that there is no learning curve for experiencing this phenomenon. The results also imply that not as many actuators are needed to achieve the perception of movement across the skin. This research provokes the notion that gestures are possible with only a few actuators. One idea is that gestural movements can be possible by starting a motion in one direction that can be completed mentally by the user.

2.2 Relevant Research

The following sections contain descriptions of relevant research in three main areas: Research on interpersonal communication in HCI provides insight on how the sense of touch is conveyed remotely. Research in the field of psychophysiology investigates how tactile stimuli can be used for communication. Work on sensory communications describes touch as used by sensory impaired people, and their use of tactile languages.

2.2.1. Haptic Interpersonal Communication

ComTouch was primarily influenced by prior work in the field of haptic interpersonal communication. This work demonstrated that technology was capable of connecting people using touch in real time. Many previous attempts to communicate touch in real time employed the use of mechanical linkages. In the early 80s, *Telephonic Arm Wrestling* introduced the idea of haptic remote communication using simulation over a telephone line that controlled levers (White 1986).

2.1.1.a Social communication

Later research focused on the interactions afforded by these devices. Fogg's *HandJive* used linked hand-held joysticks for haptic entertainment and found that tactile interaction was socially enjoyable (1998). Brave's research on computer-mediated communication provided additional evidence that the context of the device usage can either foster cooperation or competition (2001).

Due to the broadcast nature of audio and video, many existing communication devices compete for our attention. The senses can become overloaded and important information may be overlooked. The personal communication devices of others often needlessly interrupt our attention and compromise our privacy. One solution is to employ the underused modality of touch. Researchers at FXPal have focused on integrating media and modalities with research on calm technology (Nelson 2002), in hopes to soften the impact of interruption caused by current communication devices.

2.1.1.b Emotional connectivity

Several artistic explorations advanced the idea of haptic interpersonal communication by using digitally augmented objects to transmit presence information remotely, such as Dunne and Raby's presentation at *Doors of Perception* (Dunne 1994).

Exploratory combinations of various interface modalities and input-output mappings evoke awareness of a remotely located person. *Feather, Scent, Shaker* demonstrated how touch could be mapped to scents, light and vibration (Strong 1996). Ishii's *InTouch* recreated a symmetric mapping of touch over distance by preservation of the physical analog movement of rollers (Ishii 1997, Brave 1997) and described the notion of *tangible telepresence*, using touch to connect remotely located people through different mediums (Ishii 1997).

In his thesis on *personal ambient displays* Wisneski explores displaying telepresence information through tactile modalities using "thermal change (heating and cooling), movement (shifting and vibration), and change of shape (expanding, contracting, and deformation) (Wisneski 1999)." Wisneski further discusses the reasons for utilizing tactile displays to keep information private, and reducing interference with other visual and auditory activities. Wisneski's vision of *ambient* devices to transmit information in the background of a person's perception expanded on the use of ambient displays using expressive kinetic objects by Dahley (Dahley1998b, Ishii 1998, Wisneski 1998).

Following Ishii's exploration of ambient media to demonstrate information flow (Ishii 1998), physical objects were also used by Tollmar *et al.* to explore telepresence in home environments. Tollmar represents the interaction of remotely located people with everyday objects such as stones, chairs and portraits (Tollmar 2000). Further explorations introduced artifacts for emotional communication, such as the *Kiss Communicator* by IDEO used the active motion of a kiss to display colorful lights on remote objects (Buchenau 2000). *LumiTouch* is a digitally augmented picture frame that explored the passive communication of presence (Chang 2000). Grimmer's *Heart2Heart* vest allowed a touch to convey heat, pressure, and heartbeat wirelessly to mimic a physical embrace (Grimmer 2001).

2.2.2. Vibrotactile research

The design and implementation of ComTouch relies mainly on the existing body of *vibrotactile* (touch and vibration) research. Geldard first introduced the notion of applying vibrotactile stimuli to the skin, and showed that people could learn an invented tactile body language called *vibratese* (Geldard 1967). Tan, Reed and Durlach proved that the hand-based reception language of *Tadoma* could transmit very accurate information (Tan 1997). Tan further investigated the use of vibrotactile interfaces to engage the full hand (Tan 1994, 2000). Her *Tactuator*, a three-fingered sensory substitution device, used a tactile interface for improving the reception of speech (Tan 1996). Gunther's *SkinScape* used vibration devices distributed throughout the body to enhance the audio experience by immersing audience members in musically synchronized tactile compositions (Gunther 2001).

2.2.3. Tactile languages

The available tactile languages provide insight into the vast amounts of information that can be achieved by use of skin. Deaf-blind people can use a variety of tactile communication languages. *Fingerspelling* is a tactile language where the pressure and expressive movements of one hand is received on another hand. *Tadoma* is a method where the receiver places his thumbs on the lips of the speaker, with fingers on the throat. Tadoma can be so precise as to allow the user to detect intonation information from the vibrotactile stimuli (Tan 1996). In comparison, *Braille* is a static alphabetic representation coded using raised dots. "Braille can be read at 100 words per minute, slower than the rate for visual reading, which averages about 250 to 300 words a minute" (Goldstein 2002, p. 406)

Because Braille consists of discrete patterns, it can be computerized, and thus provide remote communication possibilities. However, the transmission and reception of Braille is much slower than Tadoma. Morse code, when transmitted in the form of tactile signals, is also a form of touch communication. Advanced users were able to efficiently use shorthand and perform simultaneous speech encoding and decoding of Morse messages (Tan 1996). These findings indicate that a touch-based communication language can be a very versatile communication tool.

A brief review of tactile communication languages demonstrates the potential use of touch as a primary communication medium. Deaf-blind people can use a variety of tactile communication languages.

In an overview of existing methods, Reed mentions four common traits of natural tactile communication that may be relevant in the higher rates of successful information transfer (Reed 1991): The use of the hand as the site for reception of tactual simulation, the activation of both the cutaneous and the proprioceptive branches of the tactual sensory system, the simultaneous presentation of information along a number of different dimensions, and the extensive training periods of use for a particular method.

2.2.4. Review of Commercial Products

2.2.4.a Force Feedback Devices

Assessment of the commercial products allowed us to develop an idea of technological advances and market needs. We noted the use of force feedback and vibration in entertainment devices to provide more physical interaction with computer games, enhancing the gaming experience. Some example devices are Aura System's *Interactor Vest*, Immersion's *Impulse Engine 2000*

Joystick, BSG System's *Intensor chair, VRF's Tactile Feedback System*, and SensAble's *PHANToM* (Massie 19944).

2.2.4.b Vibrotactile Perception

Commercially available vibration devices, such as Logitech's *iFeel mouse*, serve as a redundant sensory display for visual information by enabling users to physically feel onscreen boundaries. Vibrating pagers and mobile phones can subtly get a user's attention during an important meeting.

Many tactile aids for the deaf translate audio signals into vibration. Multimodal communication devices, such as the *Tactaid* device (Verillo 1992), are often used when the information transmitted using a particular single modality could be lost due to the environment or the abilities of the individual. The Optacon (Goldstein 2002, p.209) is a device that translates printed words or pictures into patterns of vibrating pins.

2.2.4.c Hand-based Input Devices

An investigation into ways in which the hand inputs information into the computer led to a wide array of keyboard devices. Doug Engelbart's 5-finger keyboard spawned many similar types of chording keyboard devices using just one hand. One popular input device used in wearable computing is HandyKey's *Twiddler*, a mobile, compact and wireless chording keyboard that allows for single-handed mouse and alphanumeric input. There are even a number of keyboards that strap to the wrist.

The existence of these devices arises mainly from a need to use the hand more efficiently (i.e. in virtual reality situations, and mobile computing). The devices are geared to maximize the use of the hand as an input method. Also, most of these devices require some time to learn before the user is proficient. This implies that any new input device will have some learning curve.

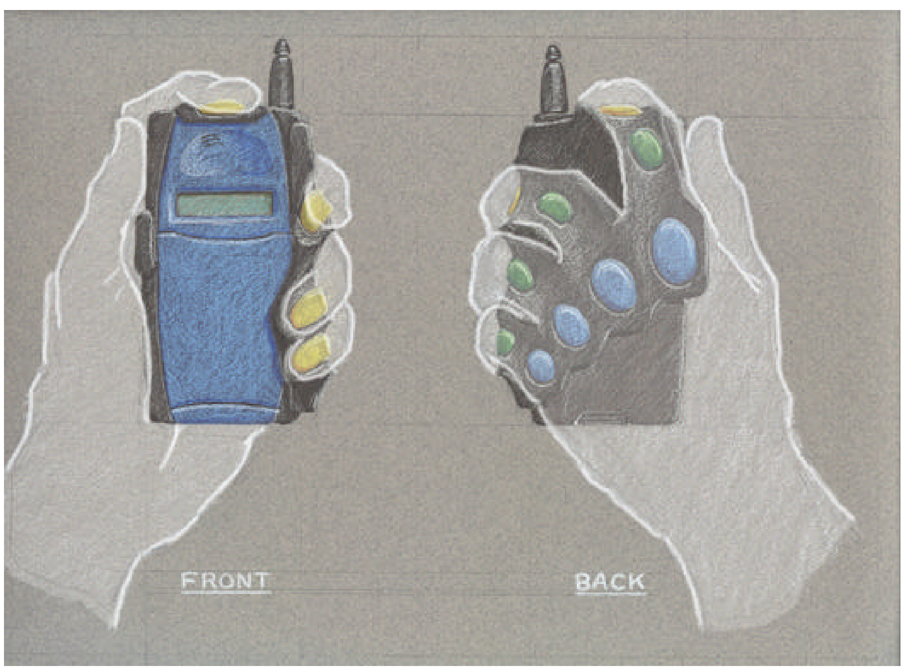
3 ComTouch design

This section will discuss a range of design issues; from high-level design principles of tactile communication, such as asynchronous information flow, to implementation decisions for aesthetic and usability reasons, like the number of buttons.

3.1 An enhancement for voice communication

The proposed device, called ComTouch, is designed to augment voice communication by translating finger pressure into vibration. The device is a cover that fits over the back of a mobile phone, as depicted in Figure 3-1. This device enables users to augment remote communication by transmitting touch. The pressure under each finger is transmitted to a remote hand. The personal nature of touch will enhance communication by allowing users to impart some physical, nonverbal information into their communication.

Figure 3-1. Artistic rendering of ComTouch Artistic rendering of ComTouch mobile phone holder concept. –Drawing courtesy of James Gouldstone



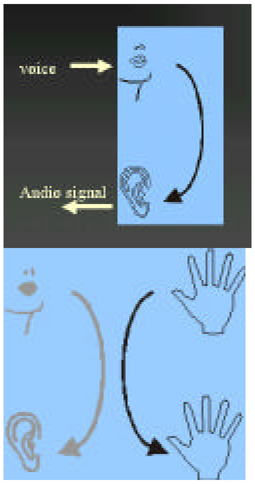


Figure 3-2. Addition of a tactile modality to existing communication. ComTouch proposes the addition of a new modality; touch, onto an existing interaction to increase the shared sensory experience in audio communication.

The approach of ComTouch is to use touch as the common sensory experience that augments existing speech communication. Our approach embodies the spirit of universal usability by creating common sensory experiences to increase communication. By increasing shared sensory experiences between different groups of the user population, communication between both the general population and users who rely on touch may be easier. Figure 3-2 shows our proposed addition of touch to audio communication.

3.1.1. Choosing the design space for tactile communication

ComTouch interactions were influenced by existing communication scenarios, particularly the telephone, and face-to-face communication. Like the telephone and face-to-face communication, the ComTouch is bi-directional and synchronous. Bi-directional describes the capability of each device to send and receive signals; the information would flow in both directions. Similarly, the device allows synchronous transmission. Thus, signals can be sent and received simultaneously, no protocol is needed for the users to transmit or receive information; signals could coincide, overlap or interrupt.

Unlike the telephone, which uses audio input and output, an asymmetric input/output mapping was chosen. Symmetric mappings of touch-to-touch in communication interfaces have been previously studied, such as inTouch (Brave 1997) and HandJive (Fogg 1998). Our approach is to explore a new asymmetric mapping using touch (e.g. touch-to-vision, or sound-to-touch). The main reason for asymmetric representations was that the signals were to be constrained to the hand, which is a small area. The parts needed to display touch symmetrically (touch-to-touch) would need to be small enough to be grasped by the hand. Representations of touch can be effective in conveying nonverbal information (Strong 1996).

In order to allow nonverbal expressive communication, the device transmits time-varying (or continuous) streams of signals rather than discrete data. In describing haptic input methods, Buxton discusses the benefits of continuous gestures that are analogous to physical gestures in communication (1983). Brave found that the emotional information is best preserved using analog, continuous signals (1998).

Figure 3-3 summarizes the design parameters of interest. We are particularly interested in bi-directional, asynchronous transmission of continuous information by means of an asymmetric interface.

3.1.2. Metaphor of Hand Gestures

The concept of this handheld device was inspired by the communication metaphor of shaking hands— a nonverbal interaction where the information is characterized by the physical nature of the participants (Ackerman). Although Geldard and

Figure 3-3 Design variables for tactile communication. This table summarizes the design parameters of interest.

Variable	*Range of design axis*	
Data direction	bi-directional	uni-directional
Data transfer	asynchronous	synchronous
I/O Mapping	asymmetric	symmetric
Data content	Continuous	discrete

Gunther both distributed vibrotactile signals over the whole body (see figure 3-4), the hand provides a compact site on the body for tactile input and output (Geldard 1967, Gunther 2002). The ability to close the sensory loop at a localized member of the body means that no extra sensory augmentation is required to both send and receive signals. Fingers can function to receive and send signals of varying degrees of intensity (Goldstein 2002).

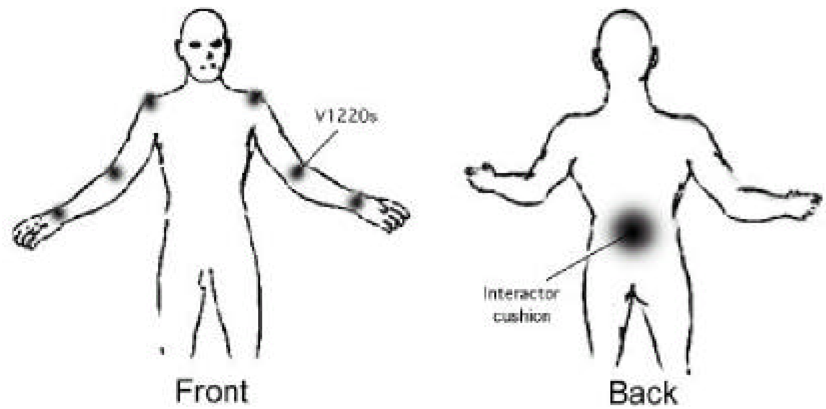


Figure 3-4. Distribution of vibrotactile signals used by Gunther's Skinscape. –from Gunther 2002 p.45.

The choice of the hand as the interface determines the number of actuators that can be used. In order to provide the maximum sensory bandwidth in the hand, we chose each finger as a site of actuation and reception. There is a higher density of touch receptors in the fingertip, while the independent motor control of each finger separately actuates a signal.

ComTouch uses all five fingers to maximize the sensory capacity of the hand to give and receive. Engaging as much of the hand as possible would allow more expression. Information theory shows that fewer degrees of expression would cause very compact messages that require much encoding, while an increased degree of expressiveness corresponds to simpler coding schemes. Because we are interested in the representation of physical gestures, such as the nuances of squeezing and motion, a close physical mapping between the fingers and the device inputs and outputs will more adequately convey physical information.

3.2 Device Specifications

Figure 3-5. InTouch transmits rolling touch by using motors gears and sophisticated control systems.

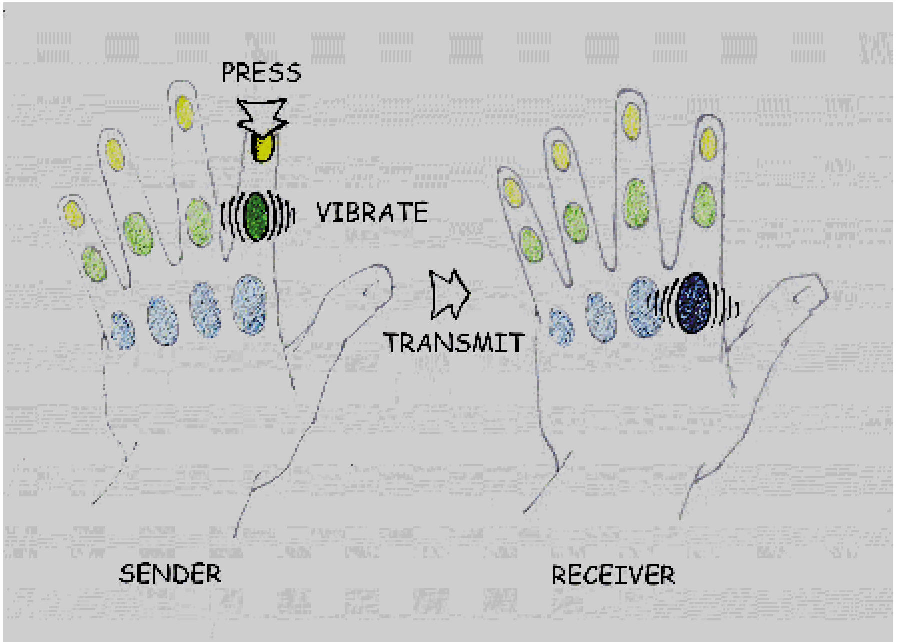
3.2.1. Vibration vs. Force Feedback

Most mechanical representations of touch, such as inTouch (in figure 3-5), are expensive to build because motors, gears and control systems are required for representing the analog qualities of touch. The number of components increases the weight of the device and makes them more suitable for stationary than mobile devices. Also, these mechanical components often wear out with use. Other possible means of force display using modern high-technology methods, such as shape memory alloys and magnetofluid, were not pursued due to expected practical problems with precision control of actuation, necessary operating conditions (temperature and sealing of components) and relatively high cost of novel technologies.

Our approach was to use vibration to represent the analog pressure of touch. The prior research suggests that vibration is the obvious choice of display. Vibrating objects are easier to hold than objects that have pushing or moving components. Vibration also was chosen because it was already implemented in many commercial communication devices. Each finger could also serve as a site to receive vibration signals.

A touch to vibration mapping was designed. A person would be able to send a signal by squeezing or pressing. The pressure of touch is then converted to intensity of vibration. This vibration would then be transmitted and felt by a remote. Figure 3-6 depicts the proposed interface.

Figure 3-6. ComTouch Touch to Vibration mapping. Notice the feedback channel and the physical separation of input/output space. –Drawing courtesy of James Gouldstone



3.2.2. Feedback channel

Sidetone: *The sound of the speaker's own voice (and background noise) as heard in the speaker's telephone receiver. Sidetone volume is usually suppressed relative to the transmitted volume.*
Figure 3-7. Sidetone definition
--From the 1006 Federal Standard 103C (Telecom Glossary)

We implemented a feedback channel for the user, so that as she communicated by pressing on the sensors there is some indication as to what was sent. In some devices, such as videophones and telephones, there is a small feedback channel (see figure 3-7 on *sidetone*) to allow users to gauge how their transmission is received. Previous research hinted that users struggled when control of a single output was shared, perhaps due to the inability of one user to distinguish her own contribution from that of her partner (Fogg 1998). As a result, ComTouch affords each user singular control over his or her output signal. Local feedback allowed users to gauge the intensity of the signal to be transmitted.

3.2.3. Sensor and Actuator Placement

The input was located on the fingertips because the flexor muscles have dynamic physical range to control a downward pressure. The output vibrations are located on the middle and base of the finger, as this area gives the most contact surface on the hand.

From the related research as well as our design rationale, the following device specifications were developed:

1. Communication using vibrotactile data. Users will be able to send data by pressure of their fingertips and receive via vibration. The squeeze force will be linked to the intensity of the vibration.
2. The device should be handheld. It is also important for the input and output areas to be localized so the hand does not have to do too much work.
3. The device should be feasible to build. The device should use components that are cheap to build, and robust in mechanical design against fatigue, wear and tear.
4. The device should be small enough for discreet use and mobility. The device should be small enough to fit in the hand, and be easy to carry.

3.2.4. Converting touch into vibration

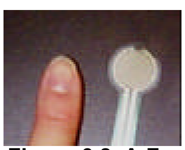


Figure 3-8. A Force Sensing Resistor. A finger is shown for scale. The FSR is made by Interlink Electronics.

Given the specification for a touch-to-vibration mapping, the circuit is designed to convert pressure into vibration.

Force sensing resistors (FSRs) measure pressure. FSRs are sensitive enough to discern a range of pressures from approximately 0.45psi (light squeeze) to 150psi (hard squeeze). Figure 3-8 depicts the FSR available from Interlink Electronics.

Figure 3-9. A V1220 Speaker actuator made by Audiologic Engineering. A finger is included for scale.

Vibrotactile research typically applies a maximum frequency of 250 Hz to take advantage of the fact that the Pacinian corpuscles, the touch receptors that are sensitive to vibration, are most sensitive to vibrations of about 250Hz (Bolanowski 1988). After trying the pager motors typical of consumer devices like the iFeel mouse, we determined that their dynamic range was too limited for adequate expression. We found a dime-sized commercial acoustic speaker quite suitable in range, and its response was quick and precise enough to represent subtle changes in the continuously varying input pressure signal. These speakers, the V1220 model from AudioLogic Engineering, are commercially used in the Tactaid device for the hearing impaired (Figure 3-9).

A touch-to-vibration mapping was implemented using a voltage-controlled oscillator (VCO) circuit. When the FSR was pressed, a voltage was input into the VCO. This signal was converted into an oscillation, and the resulting signal was fed into an audio amplifier circuit to drive the speakers. The VCO output was designed such that maximum pressure corresponded to a maximum frequency of 250Hz. Figure 3-10 displays the conversion of the signal from finger pressure to frequency of vibration through the VCO.

Figure 3-10. Diagram of one transmission from finger to vibration.

Note that the vibrotactile speakers were designed to have a very narrow frequency response, the amplitude of the output vibration signal dropped off sharply as the input frequency moved away from 250Hz, providing an effective way to create an amplitude envelope in response to changes in pressure on the FSR.

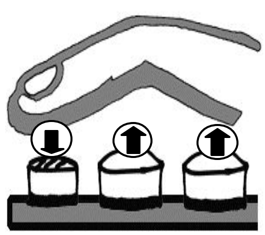


Figure 3-11. Placement of actuators on the preliminary implementation

3.3 Ergonomic Considerations

An ergonomic form factor was necessary for this handheld device. Much effort was spent on designing a handheld object where the form implied the function of the fingers. A series of prototyping, observational studies, and technical solutions were pursued. Figure 3-11 shows the layout of the input and outputs on the finger.

3.3.1. Concept generation

The basic form was a hand-held device that allowed each finger to squeeze independently. A series of exploratory form factors helped to visualize possible user interfaces. The dimensions for gripping and the elasticity of the materials were varied to gauge user preferences. More than 7 form factors were considered in the embodiment of the device. These prototypes explored features of two-handed, squeezable, ergonomic, wearable, and strapped physical interfaces. Figure 3-12 depicts some of the form factors explored.

Figure 3-12. Exploration of different form factors using rough prototypes from clay and foam.

One key issue is that the use of the device should feel comfortable and not obstruct the natural functions of the hand. In particular, the device should allow communication only when intended. For example, a user might send a squeeze signal when they are simply trying to hold the device. One solution was to use a strap for supporting the device in the users hand, or implement an on/off switch so that tactile communication must be intentional. Another solution may be to reduce the number of channels, so that some of the fingers, particularly those with less motor control such as the ring and pinky finger, could be devoted to holding the device.

3.3.2. Precision grip vs. strength grip

Observational prototyping was employed to record people using mobile phones in public. The types of grips used to hold mobile phones would inform the design of the way people hold the ComTouch. We observed that people used their index fingers to position the mobile phone. This pose allowed them to hold the earpiece against the ear, and point the other end toward their mouth.

Figure 3-13. Precision grip vs. strength grip. Precision grip uses the index finger to position an object (left). Strength grip uses all fingers in tandem (right).

Two main different kinds of grips people use (MacLeod 2000). We took some pictures to illustrate the two grips in Figure 3-13. Notice that there are two types of grips, the precision grip where the index finger is used to position an object, and the strength grip, where all the fingers act together to tighten the hand around an object. An overwhelming number of cellular phone users utilized the precision grip. ComTouch was redesigned to utilize the precision grip.

3.3.3. The nature of vibration

Masking and isolation of the vibration signals is a problem due to the compact size and localization of outputs onto a small device and contact area with the skin. The device was designed to allow 10 independent vibration signals to contact different areas of the hand. It would be hard to feel the vibration of one actuator when there are nine others nearby whose vibrations can couple either through the device or through the bones in the hand.

Figure 3-14. Transmission of vibrations through ComTouch. Undesired vibrations go through the user's body and the device, causing crosstalk. –Drawing courtesy of James Gouldstone

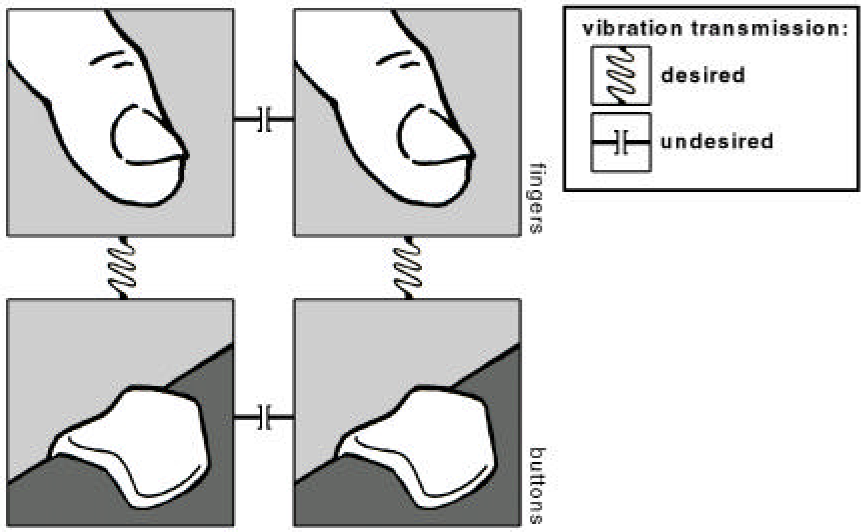


Figure 3-14 displays the transmission channels for vibration on two fingers. The desired vibrations are between the fingers and the buttons. The diagram also shows the undesired transmissions of vibrations through the user's hand (via the bones) and the structural body of the device.

Further consideration was taken to select the material properties surrounding the actuators. Rigid materials transmit vibration while elastic materials dampen vibration. It is important that the material inside the structure be strong enough to position the vibrations correctly, yet soft enough to dampen the vibration, isolating the vibration locally under each finger. The bones inside the fingers had the unwanted effect of transmitting the vibration through to adjacent fingers.

After experimenting with different types of materials varying in elasticity and thickness, it was decided that encasing the vibration units in foam would allow desirable masking and isolation of vibration. A structural device body would be made of rigid plastic, so some coupling of vibrations may be unavoidable.

3.3.4. Mechanics of the hand

The constraint of having 3 points of contact on the device would cause problems with users of different sized hands. Users with small hands would have trouble applying the maximum pressure and being able to position their hand over the reception area at the same time. The mechanics of the finger necessitate that when the sensor is pressed with the fingertip, the rest of the finger must lift off the vibrating areas slightly. This lessens the ability of the user to sense the vibrations. The most likely solution would be to design a curved and formfitting surface. This would allow the fingers to maintain contact with the speakers even though the fingertip is pressing on the squeeze sensor.

Additionally, the anatomical coupling of the muscles in the ring and the pinky finger of the hand would pose a problem, as these two fingers lack the fine motor control of the index, thumb and middle finger. The actuation and detection separate ring and pinky signals may be a problem.

3.4 Implementations

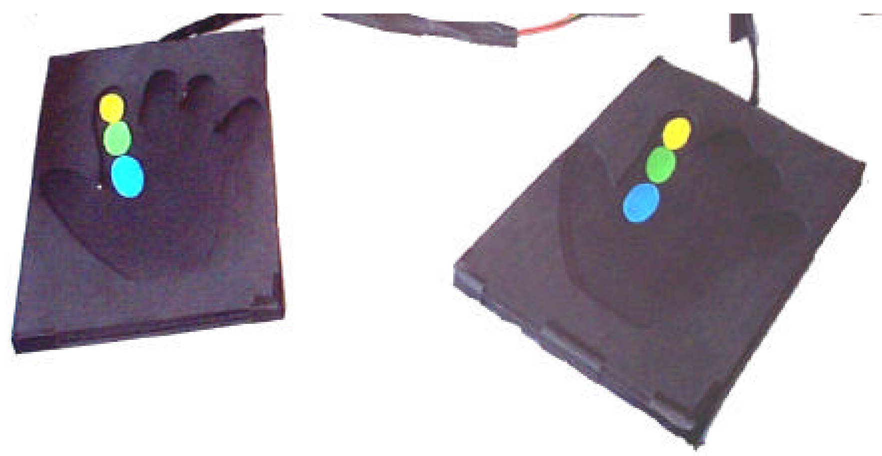


Figure 3-15. ComTouch Preliminary Implementation. One-finger of vibrotactile communication is conveyed between two pads.

3.4.1. Preliminary system implementation

Because this touch-to-vibration mapping is so unusual, a test was performed to determine whether the mapping could be used for communication. A preliminary system implementation is depicted in Figure 3.15. Colored areas helped users to understand the touch-to-vibration mapping. The prototype allows one finger to communicate using the touch-to-vibration mapping.

In this implementation, each hand rests on a plate. The tip of the index finger presses down on the yellow pad to cause a vibration in the middle of the finger (the green pad). This vibration is the local feedback signal, and allows the user to gauge the amplitude and frequency of her signal. The signal is also sent to the corresponding pad, and received at the base of the finger (the blue pad). The preliminary implementation allows two people to engage in vibrotactile communication via their index fingers.

3.4.2. Ergonomic implementation

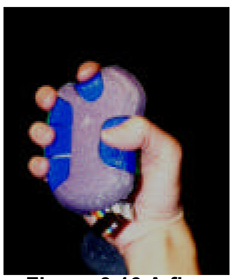


Figure 3-16 A five finger ergonomic implementation

The final implementation of the ergonomic form factor was built to fully realize the interaction design. Figure 3-16 depicts a handheld device that integrates the form design with the vibrotactile interaction. Notice that this reduces the number of contact points for the finger. The device affords the precision grip.

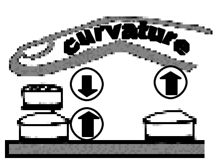


Figure 3-17 Placement of actuators in the five finger ergonomic implementation

Figure 3-17 displays a side view of one finger in the five-finger version. The main change made was the design of the ergonomic shape. We decided on a shape that would need to employ the precision grip. The shape would be small enough to grab single-handedly. The precision grip allows each finger to press independently.

Due to the constraint of the handheld surface, the touch-to-vibration mapping was slightly altered. The original location of the input force sensor and output displays confined three different points of the finger to rest on the device. This is an almost impossible fit from a human-factors standpoint. The solution was to combine the location of the input force sensor and output of the feedback signal. This compact design allows for the natural curvature of the fingers.

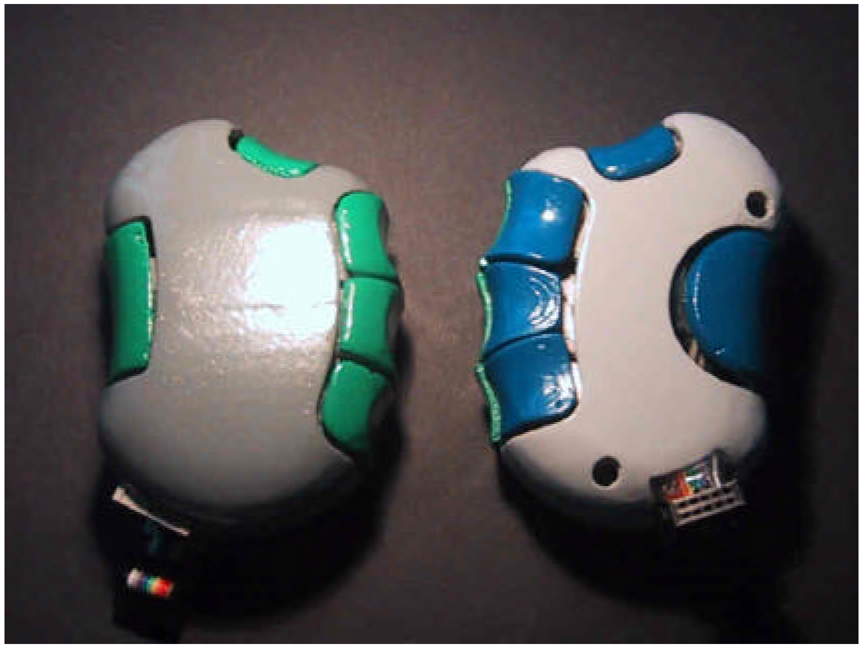


Figure 3-18. A working set of ergonomic ComTouch allowing users to use five channels of vibrotactile communication

4 experiments

4.1 Experiment on one-finger of vibrotactile mapping

4.1.1. Introduction

Experiments were designed to observe the usage of the new vibrotactile mapping. The experiments described in this section are designed to discover whether the vibrotactile mapping could support useful information. We believed that there was a relationship between audio and tactile channels. We wanted to identify the information conveyed in the tactile channel. Furthermore, we hoped to show that the additional tactile

$$\text{VOICE} + \text{TOUCH} \geq \text{VOICE} \qquad \text{Equation 1}$$

information enhances voice communication.

For simplicity, the experiments are performed using only a one-finger version of the vibrotactile device. In this experiment, participants were asked to perform two tasks, each of which was designed to discover how the tactile channel might be used. The participant's dependence on the tactile channel was varied in each task. These tasks were designed to observe the usage of the tactile channel in relationship to the audio channel, to highlight the different ways communication by touch and voice work together or separately.

4.1.2. Preliminary user studies

Figure 4-1. Preliminary user studies s showing 2 pairs of participants using the preliminary ComTouch design.

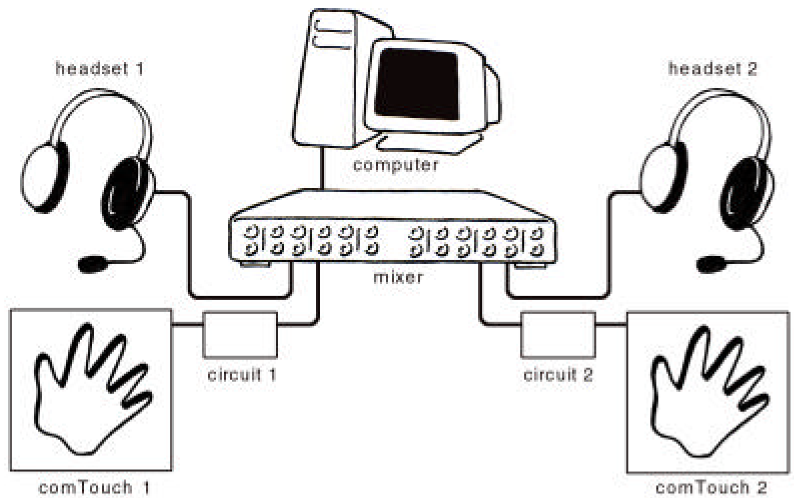
4.1.2.a Participants

A preliminary study of methods for encoding and detection of tactile information was performed. The participants were MIT college students. 24 participants, aged 18-27 (M=20), volunteered in response to a general email to MIT college living groups. All of the participants had science and engineering backgrounds. We recruited pairs of participants who already knew each other. Figure 4-1 shows two pairs running the experiment.

4.1.2.b Apparatus

The apparatus used for this study was the ComTouch device described in full in chapter 3. Each pair of participants was asked to use the one-fingered communication device (see figure 3-15) in the two communication tasks while tactile and audio information was recorded. Participants put their right hand on the device to use the vibrotactile channel. Participants would send their partner a vibration proportional to the pressure of their fingertips by pressing on the yellow pad, and also feel their feedback vibration on the green portions of the pad. Similarly, participants could feel the vibrations sent by their partner on the blue pad under their finger. Figure 4-2 shows the experiment setup.

Figure 4-2. Experiment setup



Participants wore headphones and spoke into microphones to isolate the audio signal. The audio and tactile sessions were recorded using MAX MSP software and a DIGI001 multiple-audio input mixer on a Macintosh G4. Using MAX MSP, white noise was added to the subject's headphone outputs to allow better hearing of the audio conversation by masking out the noises from the device and the environment. Participants were positioned facing away from each other such that they had no visual contact. After the experiment, the data was reviewed using Sonic Foundry Acid™, a program that allows simultaneous review and replay of all four channels.

4.1.3. Experimental Procedure

The experiments use two scenarios: a general talking scenario and a negotiation scenario. The talking scenario allowed the users to talk freely over an audio link, with an additional tactile channel. The negotiation scenario allowed more emphasis of the tactile channel. In the negotiation scenario, the participants were encouraged to use the tactile channel to agree on a ranking of 5 things out of a list of 15 items. The conditions were organized within-subjects, as everyone participated in all scenarios.

The first task, a **chatting task**, was designed to observe whether the participants could use the tactile channel, and to monitor how the device would be used without specified instructions. After a brief explanation of the device, participants were asked to chat for 5 minutes. Some preliminary topics were given as conversation starters, but subjects were allowed to deviate from these topics. The first task allowed participants to partially overcome the novelty of the device by using the tactile device as a supplement to audio. If the participants finished talking about the suggested topics before the time limit, they would just keep talking until the end of the duration of the task. Audio and tactile data were fed via a DIGI001 hardware interface to a Macintosh G4 computer, which recorded the data.

The second task**,** a **negotiation** task, was devised to get participants to rely on the device to communicate specific information to each other. The test used a scenario called the Desert Survival Problem (DSP). DSP is commonly used as a negotiation skills task (Bonito 1999). The DSP scenario gives the users a context in which to use the device; they are stranded in the desert and need to get to safety together.

The participants were given 5 minutes to individually rank a list of 15 survival-related items in order of importance. They were then asked to rank a smaller set of 5 items together using mainly the tactile channel. During the collaborative ranking task, we monitored their audio communication channel in case they had to resort to voice communication.

This second task gave users some incentive to use the tactile device and avoid the voice channel. The participants were told that the use of the voice channel was insecure, and could be overheard by enemies. When the participants engaged in too much voice conversation, they were warned using a printed sign that enemies were in the area to further reinforce the need for using the device. This artificial penalty for use of the voice channel was designed to emphasize use of the tactile channel. A time limit of 10 minutes was given to apply time pressure in order to speed up negotiation. Again, voice and tactile data were recorded for this interval.

When the subjects were finished ranking the items, they answered a questionnaire designed to obtain feedback about the experiment and their communication methodology. An exit interview was performed where subjects were asked for extra feedback on the device and tactile interaction. All answers were recorded verbatim and categorized on a spreadsheet. The two audio and tactile channels were later replayed and graphed. A reviewer marked the occurrences of interrelation between both channels.

4.1.4. Criteria for evaluation

Occurrences of interaction between the audio and tactile channels in 12 trials (two tasks per trial) were marked. All 12 conversations were replayed on Sonic Acid™. Reoccurring patterns were categorized and marked. The criteria for judging occurrences of interrelation between audio and tactile data are described as follows:

- *Emphasis* was noted when the intensity and timing of the tactile signal coincided with the audio signal. The rise and fall voice volume and the tactile intensity occurred at the same time.

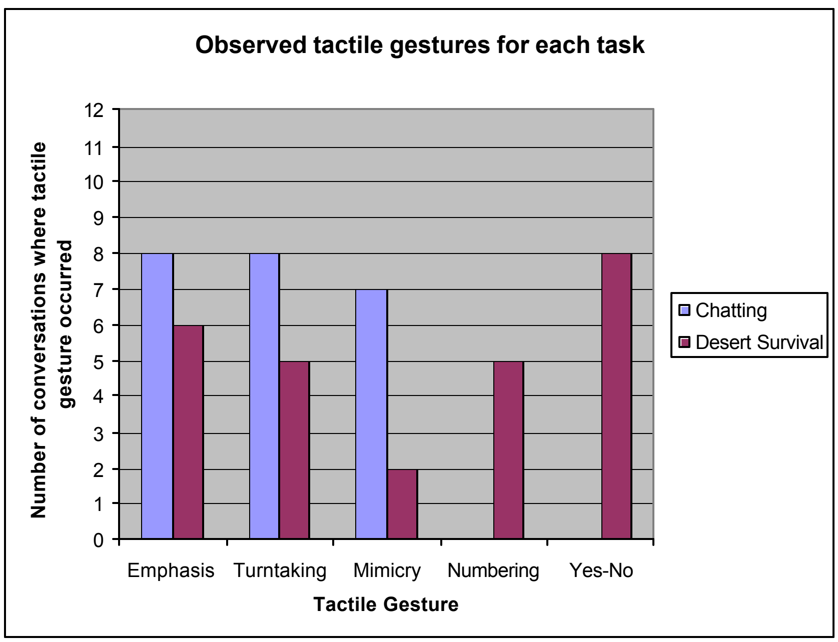
- *Turn-taking* was identified whenever the tactile signal was used to begin or interrupt the audio signal. In tactile turn-taking, the person who spoke preceded their audio signal with a tactile press. At times, the tactile press was used to interrupt the other participant's audio signal and the interrupter would then interject her own audio signal.

- *Mimicry* was detected when the users repeated patterns back and forth, and the patterns did not coincide with the information in the audio channel.

4.2 Results

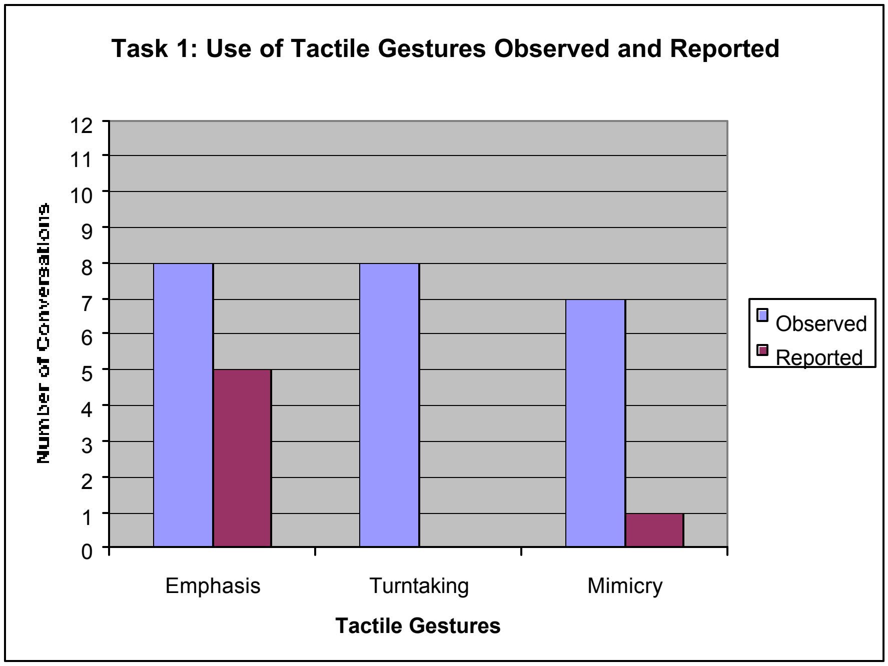
Patterns in the signal data clearly indicate that subjects employed 3 meaningful *tactile gestures*, or representations of touch for expression, which we call emphasis, turn-taking and mimicry. In addition, participants developed encoding schemes for transmitting data in the second. Figure 4-3 shows a tally of the observed patterns.

Figure 4-3. Resulting observed tactile gestures for each experiments. The total number of conversations exhibiting tactile gestures at least once for each task.



4.2.1. Results of the first experiment.

Figure 4-4. Number of pairs exhibiting tactile gestures in first task compared to number of pairs that reported usage of tactile gestures.



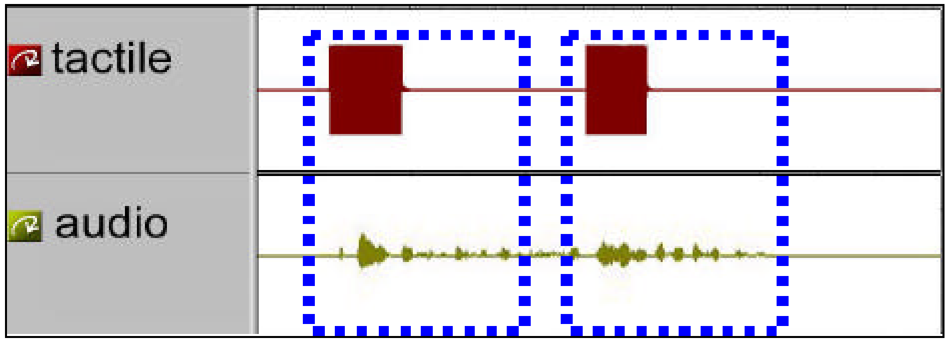
In the first task, participants learned to use the device quickly, and were able to talk freely using the device without asking for help. Most users spent only a few seconds testing and talking about the buzzing before moving onto other conversation topics. Figure 4-4 displays the number of conversations that showed tactile gestures the first task.

4.2.2. Emphasis

Participants often synchronized their tactile pattern to their speech, in order to emphasize their message. Only 5 out of 24 participants reported an awareness of using the tactile channel for this purpose. Emphasis was the most frequently observed tactile gesture, and was observed for 8 of the 12 conversation trials.

Emphasis occurred in the observed pattern when peaks in the amplitude of the tactile signal coincided with stressed words in the voice data. Many of the trials contained repeated use of emphasis. Often, the speaker would press and talk at the same time to highlight a phrase (Figure 4-5). The audio rhythm and tactile signal sometimes occurred at the same time of speech, to give the effect of the tactile information accenting certain syllables. The redundant tactile information drew the listener's attention to particular spoken words or phrases.

Figure 4-5. Emphasis of the audio channel is shown as the user presses to draw attention to certain words.

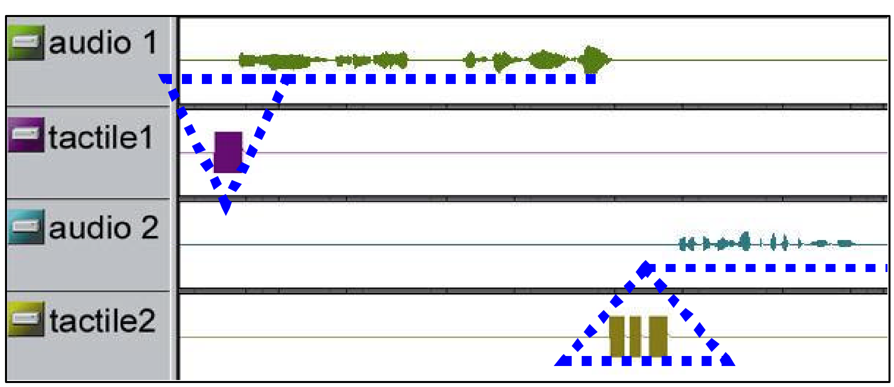


4.2.3. Turn-taking

Turn-taking cues are auxiliary information to aid in the flow of conversation. Glances, gestures, or speech pauses are typical turn-taking cues to pass the flow of conversation onto another person. In 8 of 12 conversation trials, participants appeared to use the vibrotactile signal as a turn-taking marker. A press or series of presses was often given before the subject spoke (Figure 4-6). These signals were sometimes used to interrupt the other speaker to signal that the other participant intended to speak. However, participants did not indicate such a usage in their reports.

In the trials, the tactile signal allowed users to indicate a desire to speak by preceding comments with a buzz. Note that this use of the tactile signal was not redundant to the audio signal.

Figure 4-6. Turn-taking markers. Each person takes a turn by preceding audio with tactile presses.

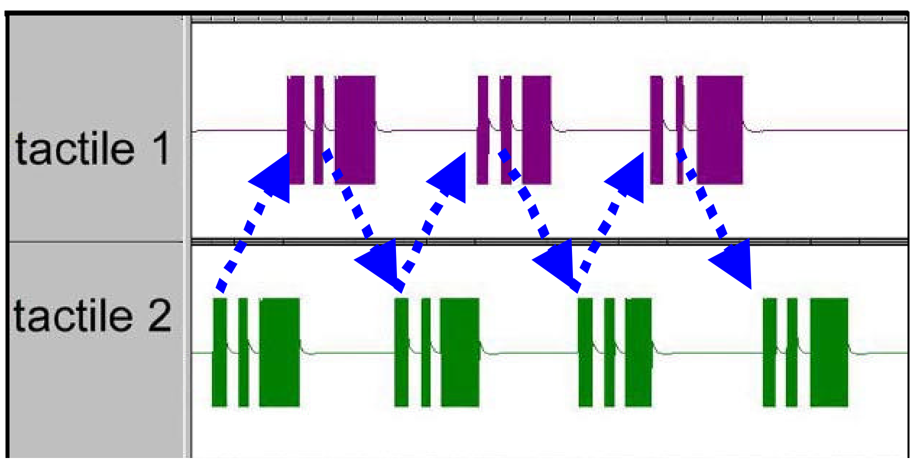


4.2.4. Mimicry

Participants tapped out a complex pattern and echoed it back to one another (Figure 4-7). Rhythm, duration and intensity of the first pattern were duplicated in the second. These patterns sometimes happened in silence, sometimes in conjunction with an audio signal that was independent of the tactile signal. Mimicry was observed at least once in 7 out of 12 trials.

Four participants reported using the channel to send echoes to one another. According to these participants, this information served as a means of ensuring their partner's presence and attention. The tactile signal took the place of nodding or verbally signifying that the other person was listening. Other participants claimed that this behavior was an extension of physical interactions they had, e.g. patting each other on the arms as a form of camaraderie.

Figure 4-7. Mimicry patterns are echoed back and forth, independent of the audio.



4.2.5. Encoding

In the second task, the desert survival task, voice interaction was intentionally limited. There was an observed decrease in the number of conversations exhibiting the emphasis, turn-taking or mimicry. Participants reported the method of their encoding schemes. The data confirmed that subjects devised tactile encoding schemes during the second task. Using different durations of taps for agreement was observed in conjunction with summing the occurrence of a succession of taps to represent a number.

All 24 participants successfully completed the negotiation task. 8 out of 12 pairs of participants devised a tactile encoding system. The use of a binary “yes-no” scheme was seen 8 of the 12 pairs. Additionally, 5 pairs of participants devised a numbering scheme for indicating the position of the list items. Four pairs of participants used both schemes. Figure 4-8 shows a tactile communication example of a numbered suggestion, with a binary reply.

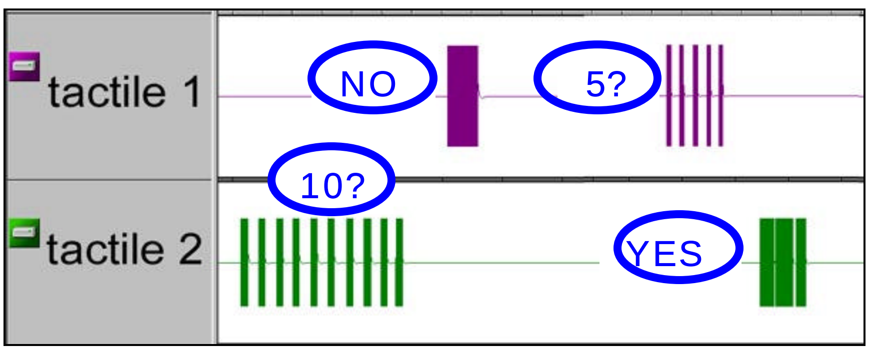


Figure 4-8. Encoding schemes. A numeric encoding pattern and an agreement arrangement is shown. A single long press means no, while three long presses means yes.

4.3 Discussion

The central finding of the preliminary study is that there is a range of correlation between the voice and tactile communication channel. As expected, the information transmitted over the tactile channel proved to be meaningful.

The results of the chatting task demonstrate the existence of tactile gestures when subjects are provided with a tactile channel in addition to voice communication. In relation to voice, the information transmitted over the tactile channel ranged from independent to redundant. Emphasis, for example, is a redundant gesture. Syllables and words already stressed orally were additionally weighted with a buzz. Mimicry, at the other extreme, was largely independent of the voice channel. Turn-taking falls somewhere in between the two. On the one hand, a buzz can serve to highlight the beginning of a speech. On the other, a buzz unaccompanied by audio can indicate impatience born of the desire to interrupt.

The negotiation task demonstrates that information can be structured and sent via the tactile channel in such a way as to make voice communication less or not necessary. The existence of numerous tactile communication languages supports this finding. This is surprising because the touch-to-vibration mapping is a new mapping, and users were not instructed as to how to use the interface. Nevertheless, approximately 70% of the users reported establishing their own coding schemes.

Although some participants reported being confused by the unspecified purpose of the tactile channel, the data indicated that almost all subjects employed at least one of the three tactile gestures.

These results shed light upon the possible benefits of a tactile communication device in everyday use. A touch-based device can provide an informative and private way to augment existing communication. For example, one might wish to remain connected even when in a place where voice communication is inappropriate such as inside a library. Touch based communication can allow discreet notification of personal messages without broadcasting an interruption to others.

Although much care was taken to design the test to be as simple as possible, there were some improvements that participants reported could be made on the device.

4.3.1. Ergonomics

Approximately half of the participants reported that their use of the device was affected by the lack of ergonomics in the device. Users with small hands reported having trouble applying the maximum pressure and being able to position their hand over the reception area at the same time. The mechanics of the finger necessitate that when the sensor is pressed with the fingertip, the rest of the finger must lift off the vibrating areas slightly. This lessens the ability of the user to sense the vibrations. The most likely solution would be to design a curved and formfitting surface, instead of a flat plate. This would allow the fingers to maintain contact with the speakers even though the fingertip is pressing on the squeeze sensor.

Three participants were left-handed. Although it was expected that there might be problems with left-handed users adapting to the right-handed pad, none of these participants reported problems in using the device.

4.3.2. Lack of resolution of vibration intensity

Although some participants were able to perceive and use the dynamic range of the channel, approximately half reported that the resolution of the vibration seemed to have 3 states- high, low and off. This may be related to the aforementioned ergonomic concerns.

4.3.3. More channels please

More than half of the participants expressed a need for more of the fingers to communicate. Although subjects could not clearly indicate why they would need to engage more fingers, most felt strongly that engaging only a single finger was limiting.

4.3.4. Audible Vibration

In the test, the noise of vibration was masked by white noise in the headphones. However, there is an audible buzzing as a result of the vibration of the vibrating elements against the material restraints. The audible buzzing is due to the nature of the vibration, and could be a problem when using the device in conjunction with audio. Some development will have to be to mask the vibration from the audio signal.

4.3.5. Limitations

Some limitations of the study should be addressed. One constraint is the need to account for the novelty effect[1], as users will be inexperienced with vibrotactile stimuli on the skin (Brave, 2001).

4.3.6. Subject familiarity

The results depended mainly on the existence of good communication between the pairs of participants. The pre-existing relationships between participants affect the results of the study in two ways. First, the participants in each trial were very familiar with one another. Thus, no claims may be made about the potential for successful tactile communication between strangers. Second, visual contact between participants was eliminated by the experimental design. The availability of a visual channel may have lessened the reliance on the tactile channel.

4.3.7. Data Analysis

The data analysis here was very conservative. The analysis merely looked for occurrences of overlap or rhythm between the audio and tactile channels in each trial. If at least one occurrence was found, it was reported. The actual occurrence of the tactile gestures was probably more prominent, as incidences of certain gestures were repeated in many cases. However, the existence of 2 gigabytes of audio data, consisting of 96 streams allowed only casual examination of the data. Only had one person analyzed the data, so there was no real statistical analysis. In essence, tactile gestures occurred far more frequently than reported.

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[1] The Novelty Effect is described as an effect that occurs when learners are stimulated to greater efforts simply because of the novelty of treatment. As the treatment grows familiar, it loses its potency (Brave 2001).

Also, the three identified gestures did not describe all the vibrational gestures used. Some other gestures created were highly reliant on implied meanings in tactile communication channel. For example, in one incident, the user asked teasingly "what did you do this weekend?" and then the user asked again using a series of buzzes. The response was "nuh-uh, not **that**!"

Another interesting usage was the use of tactile gesture to substitute an affective expression. A few users were observed substituting laughing or squeezing for pressing.

4.4 Summary of first experiment

The previous section presented our findings on the observed usages of the tactile channels. These findings confirm our hypotheses about the value of touch communication. The data shows that tactile information does enhance audio communication by providing additional information. This additional tactile information can work together or separately with audio information, by means of the three tactile gestures described. The significant finding is that users can detect vibrational feedback in conjunction with, or without, verbal feedback.

We have also verified that the new vibrotactile mapping is capable of relaying interesting information. Although this vibrotactile mapping is not the most intuitive (as direct actuation), it conveys enough information to allow expression of nonverbal cues. These results raise the possibility of the development of communication schemas using this particular mapping.

We began to realize that there was much future work to be done to show how a tactile language could be developed. A series of reoccurring questions have appeared thematically in this research concerning the nature of tactile communication. We had to make educated guesses about these issues, and we state the theories of a tactile mobile language in the next section.

5 the potential of tactile gestures…

5.1 Introduction

We were initially focused on advancing the state of the art of remote communication. Pagers and mobile telephones already contain vibrating elements to indicate when the phone is ringing. Extending that capability to provide more information appears to be a sensible idea. A device that conveys more degrees of freedom (e.g. representing the touch of each finger) might allow for more expressive interactions.

5.1.1. Potential Users

We were interested in providing potential users with new means of expression by employing a new modal addition to an old communication channel. Who would be the potential users of vibrotactile communication? To gain insight on the existing needs of potential users, we studied users of existing tactile communications. We found two relevant groups of people, the sensory-impaired (particularly the deaf-blind community who rely on touch for communication) and current remote communication technology users (figure 5-1).

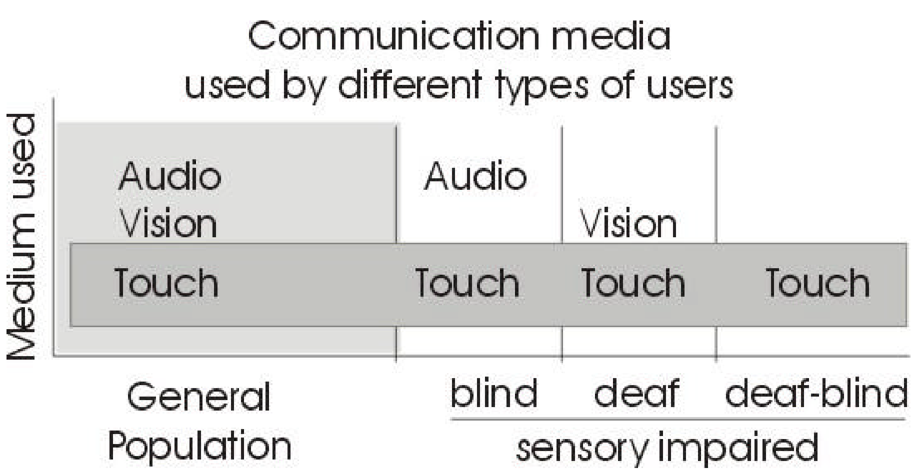
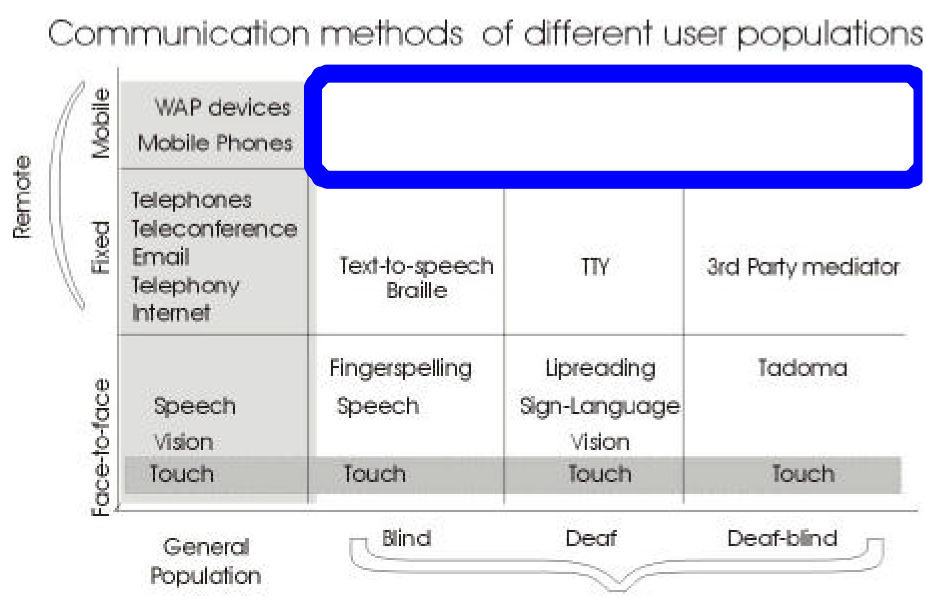


Figure 5-1. The common sense of touch. Touch is common among the general population and sensory impaired people.

We also found that there was no remote mobile communication method for the touch-reliant population (figure 5-2). As suggested in the background section, we found that deaf-blind people use touch-based languages in face-to-face communication (touch cues, gestures, sign language, fingerspelling, signed English, signed pidgin, Braille writing and reading, Tadoma speech reading, American sign language). We were particularly interested in transmitting the expressive qualities of fingerspelling. However, we found that the there is no international standard for touch communication among this population; e.g. although Braille is the closest "standard" it required from 6 to 9 months of training and the percentage of the blind population that can read Braille fluently is decreasing (Dobbs 1999). Furthermore, for remote real-time communication, the deaf-blind normally use a third party to mediate their conversation. Existing remote communication devices using Braille displays available to the blind are costly. Another problem with existing communication devices is that there is a large learning curve. We hoped that the device we build would allow mobile technology to be more accessible for this population.

Figure 5-2. Existing communication methods for different user scenarios. Note the lack of remote communication methods for the sensory impaired.



From interviewing of the kinds of tactile input and output mappings that would be suitable to blind people, we found that glove-like devices were not ideal because of the constrictive nature. Our potential users expressed dislike of force-feedback devices because of the difficulty in overcoming the feedback force to communicate. There was also the concern of unintentional injury due to the force applied by a machine; for example, if a force-feedback glove forced the hand into an unnatural position.

As discussed in Chapter 2, Tadoma, tactile sign language (the tactile version of American Sign Language) and fingerspelling are existing tactile languages. Although these have all proven to be somewhat effective for a community with the need and motivation to learn them, there is currently no easy, established tactile language that can be adapted for a wider user community.

While focusing on communities that relied on touch gave us insight as to the existing tactile communication methods, we desired mostly to enhance mobile communication in general. Morse code was another method of communication (not a language) that could be transmitted in any form – using flares, lights, flags, sounds, or vibrations. The tactile version of Morse code explored by Reed, was interesting because of its widespread use. The established use of Morse code for transmitting messages through telegraphs since 1901, usage by a diverse population (from boy scouts to military servicemen) shows us of the great potential for tactile communication.

5.1.2. Adoption of potential languages

There is currently no easy, widely adapted tactile language. We therefore focus in this work on developing a device that would allow a universal population of users to exchange merely a "sense" of touch, rather than attempting to design a set protocol for communication.

Many reasons exist for not adapting an existing tactile language. First, we found that existing tactile languages were not exactly transferable to the device we had in mind. Second, existing tactile languages were not widely used to be a compelling fit for the envisioned device. Third, we felt that existing tactile languages like Braille, one-handed Braille or chording one-handed keyboards, had too high of a learning curve to be widely adaptable. Lastly, the recent rise of simple text messaging on cell phones provided us with hope that the new communication schemes are possible. The example provided by SMS, gave us reason to believe that a vibration language may arise out of common use, developed by users.

5.2 Development of a touch language

"The problems of control engineering and of communication engineering were inseparable, and that they centered not around the technique of electrical engineering but around the much more fundamental notion of the message."— Norbert Weiner, Cybernetics (page 8).

5.2.1. Basic components of vibration communication

A large body of psychophysics[2] work exists on determining the proprioceptive mechanics of the sense of touch and vibration. This previous work is concerned with determining characteristics such as the maximum frequency of skin sensitivity to vibration, as described in the background section. From this material, it is necessary to examine at a higher level the use of touch in communication. Specifically, whether a language can be developed for vibrotactile touch communication.

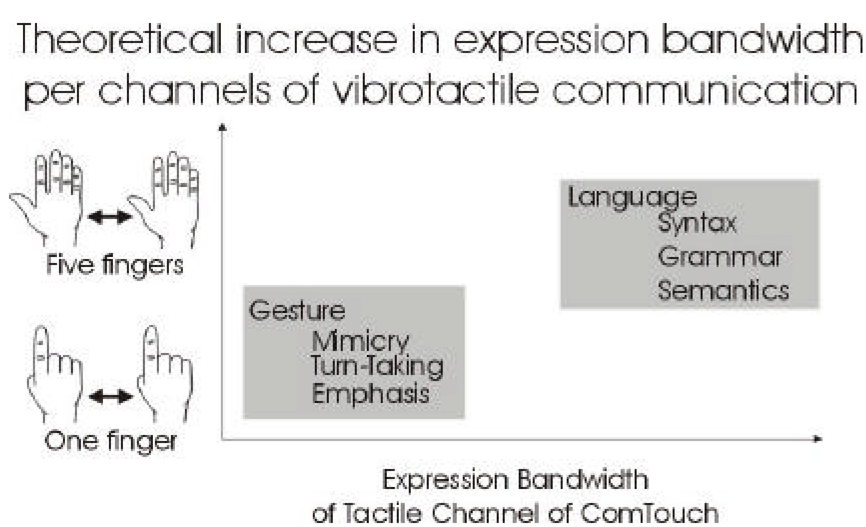
In his thesis entitled *Skinscape: A Tactile Tool for Music Composition,* Gunther presents an overview of frequency, temporal

[2] *Psychophysics* is the scientific study of relationships between physical stimuli and perceptual phenomena. –MIT Encyclopedia for Cognitive Science

structure, dynamic range of intensity, and spatial distribution of signals (Gunther 2001). The information content of touch is dependent upon the bandwidth and the complexity of the communication channel. The bandwidth of ComTouch is five fingers. The basic component of a signal is the squeeze force (dynamic range) and duration (temporal structure). The combination of intensity, duration, and spatial distribution of signals (choice of fingers) will provide the primitive tools for construction of messages. The speed of transmission provides the syntax (e.g. pauses, vibrations per second), while the intensity of the vibration (from subtle to intense), combined with the use of available fingers provides the grammar for communication. There can be many various levels of complexity, ranging from keying strokes, to the more multifaceted variations, like using a mix of the different intensities, fingers, and voice contribution to the message.

The amount of available combinations of channels is related to the possible information that is available to be communicated. It appears that an increase in channel capacity corresponds to an increase in complexity. Figure 5-3 depicts the design space for tactile communication in relation to the tactile channels in ComTouch.

Figure 5-3. Expression increases with the number of channels.
Increase in expressive bandwidth content per channels of vibrotactile communication.



5.3 Communicating emotion

A large series of questions concerned how would users communicate ideas? Should the language being communicated be alphabetic or conceptual? Examples of alphabetic language devices are chording keyboards; text-based communications, and telegraphs. Examples of conceptual languages are voice communication, hand gestures, and body language. We believed that the tactile language would be able to support both conceptual and alphabetic meaning. We were more interested in conceptual meanings, as the device was meant to focus on emotional content.

We feel that although it is quite possible to build a device like the HandyKey *Twiddler* device and single-handed keyboards, to encode what Gunther would refer to as *hard information*, we are more interested in conveying the abstract qualities of touch. Furthermore, the availability of the audio channel for voice communication puts less reliance on the device to convey hard information. Ideally, a touch language would convey both types of information. However, we feel that the intended users of the device would definitely want to use it for emotional information.

Emotional information is the desired type of message, because its abstract qualities can map to the emotions. We leave the hard information of facts to the more distinctly informative channels of text and voice. We leave the graphical information to the high data transfer rates of the Internet. In effect, emotional information maps well to touch because of its subtle qualities.

5.4 Touch Communication Scenarios

We designed our device to allow people would use this low-bandwidth, analogous channel. How can a touch-to-vibration channel be used to communicate this nonverbal information? The evidence of the three tactile gestures, shows us just a hint of what kind of information could be used. Another question is how to envision the correct application to illustrate the usage of tactile communication.

5.4.1. Messaging Application

A specially designed vibrational messaging application could exploit this capacity for diverse types of personal content, communicating both complex meanings and simple ideas.

Users could map different vibration patterns that identify who the caller was, i.e. the type of vibration would indicate friend, business, lover or family if your address book is programmed for it. Alternatively, the phone caller could use a code when dialing to indicate the priority of the call (urgent or not urgent, confidential, etc.) and thus it would vibrate in a different way for each situation. Another idea is vibration for predefined messages, similar to SMS (Short Message Service or short text message), where users would have a “dictionary” of available vibrations and their meanings.

5.4.2. Emotional aspects of tactile communication

One particular vision we have is for touch to be used to remotely communicate emotional behavior. Loved ones often want to communicate personal messages. If the modality of touch is available, being able to express higher-level emotions might be desired. This idea would be similar to emoticons conveying emotional information in text-based systems. For example, as a lover expresses good-bye, the squeeze would emphasize the emotional content. If the squeeze was hard, then it might signify a strong love, if it was a light touch, it might signify a reassuring, soft pat. In essence, the tactile channel would allow expression of intensity of emotion.

5.4.3. The use of touch in mobile communication

Touch can act in two capacities in mobile communication. The first is as an a sensory augmentation to the voice channel. The second, when touch stands alone, is more dependent upon the bandwidth and complexity of the touch channel.

5.4.3.a Augmentation to voice

In the experiments described in Chapter 4, touch was shown to augment voice transmissions. The nature of touch will allow personal content to be conveyed in a private manner. In situations where audio communication cannot convey emotion, a touch-based device can provide a channel for this type of communication. Touch based communication can allow discreet transmission personal nonverbal signals under the cover of audio. Two people could convey information privately while having an open audio channel. One thought is that the touch channel will act as an extension of the physical body space. In a business setting, people could shake hands at the end of a conversation. In a more private setting, close relationships could be signified by meaningful squeezes, and tactile hugs. The tactile gestures of emphasis, turn taking and mimicry would be employed.

5.4.3.b Touch Stands Alone

Where audio communication is impossible, a touch-based device can provide a private channel for communication. For example, one might wish to remain connected even when inside a library. Touch based communication can allow discreet notification of personal messages without broadcasting an interruption to others. One possible scenario is that people might send Morse codes to each other in lieu of audio when it is too noisy to communicate. Two people at a concert might be able to arrange to meet by tapping out their location because visual contact is broken.

When the deaf or hearing-impaired users are considered, then communication can be expected to rely mainly on vision or touch. Touch has advantage in allowing this community more privacy. The ability to share a touch signal would allow private collaboration when compared to broadcasting sign language in a public place.

Furthermore, the mobility of touch can enable greater communication for deaf-blind users. Among remotely located deaf-blind users, existing technologies limit the ability for the deaf-blind to communicate with one another due to the face-to-face nature of touch. In addition, the mobile transmission of touch will enable communication between two previously separate populations. In a wireless touch-based communication system, a deaf-blind person could use the common sense of touch to communicate remotely with anyone.

5.5 Additional potential of touch communication

The following sections describe some features of touch that are of interest in this research. When people are given the ability to simulate touch over a vibrotactile interface in the context of communication, some interesting properties of touch can be studied. We hope to observe the emergence of patterns and encoding schemes as listed below.

5.5.1. Cutaneous Illusions

The sensory Saltation phenomenon, also called the "cutaneous rabbit" describes the illusion of movement as a result of patterns of stimulation over an area of the skin (Geldard, 1972). The variation of location of vibration can allow gestural information to be displayed. The variation of duration and gaps in the signal may be relevant to the display of tactile stimuli. The ability to stimulate the illusion of movement across the skin using vibration, discovered by Geldard and Sherrick (1960) may provide a means of conveying nonverbal gestures.

Gunther's distribution of speakers across the body's surface allowed special effects of music to be displayed on the user's skin.

Members of the audience at a musical performance who wore Gunther's devices experienced a sense of the movement of raindrops across their arms, or motion throughout the body using vibrotactile stimuli. In the ComTouch device, users might be able to feel the tapping of their partner's fingers to music, to show the location of a rhythm (perhaps in a piece of piano music), or to gesture—e.g. indicate the movement of something across one's fingers.

5.5.2. Coding of alphanumeric content

The sense of touch has been proven to be effective for transmitting hard information, such as the tactile body language invented by Geldard (1967). The methods of transmission, reception, and recognition of tactile patterns were detected with much training. Numbers and alphabetic content were successfully transmitted and received, hinting that a hand-based vibrotactile language can also be developed.

In the ComTouch, the sensations are confined to the hand. However, the success of one-handed devices show that learning to code alphanumeric content is possible. Perhaps the fingers of the hand, and the intensity of squeezing will designate keystrokes. Another possibility is the adaptation of chording the fingers, such as employed in Engelbart's one-handed keyboard.

5.5.3. Multiplexing of Tactile transmissions

In places where remote communication already takes place, touch devices can allow people to further their range of communication by multiplexing existing communication channels. The low attention requirement of ComTouch might allow users to have a spoken conversation over the phone that is entirely different from the tactile message they are sending.

The ability to sustain multiple threads of communication using only the sense of touch, as exhibited with Morse code, may be transferred to vibrotactile communication (Tan 1997). Symbolic and alphabetic language can be combined in a language. For example, Morse code is one example of such a combination of methods. In one study of Morse code, users started out by learning letters individual letters. As the time of usage increased, a symbolic language emerged and it then became hard to distinguish individual letters in transmission. Furthermore, users were able to recognize whole sentences using shorthand and able to perform simultaneous translation of speech in addition to decoding Morse messages (Tan 1997). Perhaps simultaneous multiple tactile conversations will one day be possible using the ComTouch.

5.6 No vibrotactile language for ComTouch yet

At this time, we have not developed a language for the ComTouch. However, we do not think it is appropriate to design this language. The simple reason is consideration for the user's freedom of expression. The goal of the device is to communicate a sense of touch, and we feel that the meanings encoded by the user should be left up to the user. Another approach, however, is to develop a standard to coordinate how people communicate. We feel the latter approach may come later, as a result of further scientific investigation into vibrotactile communication techniques.

We believe there is a good possibility that a language may arise out of repeated usage of this device, similar to the way SMS and pager codes have been developed. By allowing users to create their own communication schemas is the best method for utilizing touch communication. A recognized standard, akin to Morse code would have the problems mentioned earlier—high learning curves and standardizing usage among people who may want to use the device for different reasons.

Allowing users to adopt their own approach minimizes the learning time for that user, but the other communicating partner may need to learn how to translate the gestures. We realize that the lack of a benchmark standard to compare to will allow users freedom to compose and invent their own gestures, thus enabling a wider range of expressive techniques. The conclusion is that we want the expression to be as personal as desired.

6 conclusion

The research presented in this dissertation evaluates the potential of a proposed vibrotactile mapping as a medium for touch communication. The strength of the ComTouch project lies in its use of integrated modalities of touch and audio. Integration with audio provides some insight on the use of the tactile channel. Experiments proved that the physical representation of touch is transmitted provide some nonverbal cues, called *tactile gestures*, not available in remote audio communication.

6.1 The Vibrotactile Mapping

The scope of this study is to determine whether vibrotactile cues can convey information that enhances remote voice communication. This study does not aim to develop a tactile substitute for the telephone, but rather, to examine both the nature and amount of information a vibrotactile channel can convey when added to an existing audio channel. Evaluating the vibrotactile contribution is merely the first step of research in how this information can be used in remote communication. This investigation is interested in exploring the role of vibrotactile information for sensory impaired communities, and creating a tool that can be universally utilized using the common sense of touch. Also, this research does not propose to invent a vibrotactile communication language, but suggest how a tactile language might be used.

Preliminary user studies provided insight into the characteristic uses of a device that transmits tactile signals simultaneously with audio communication. The touch signals were shown to enhance audio conversations by providing redundant and independent information in the form of *tactile gestures*. These gestures presented nonverbal cues that can be lost or overlooked when strictly audio is used.

Within moments, people new to the device were able to communicate through the tactile channel in a non-trivial and successful way (i.e. using mimicry, emphasis and turn taking). In the future, a longer-term study would be needed to reveal if and to what extent interacting with vibration affects communication. These types of studies are much more challenging, since it is difficult to trace the contributions from a specific person's gestures to the creation of a new common set of expressions.

We hope that this kind of research will contribute to enabling mobile communication for the sensory-impaired population one day, in addition to enhancing existing communications for the current population of mobile device users by adding the underused sense of touch. Understanding the nature of touch and its role in communication may eventually inform the development of a touch communication language.

6.2 Future Work

The design decisions of ComTouch were selected with the goal that this research might one day inform the design of a tactile telephone. The underlying goals of low cost, robustness to fatigue, and small size were factors that made vibrotactile actuation a likely candidate. The consideration of users needs led us to design the feedback channel, and ergonomic shape of the final device. Meanwhile, a large portion of research in existing communications work was carried out and incremental evaluation by peer review was performed throughout the process of development. Much iteration of prototyping and deductive engineering went into the successive prototypes. The reason for so many reviews, iterations, and changes was because we were doing work of interest to researchers in many fields, and at the same time dealing with the complex problems inherent in combining such diverse fields of thought and engineering.

A number of suggested hardware changes and alternative mappings are presented below to guide future work on tactile communication.

There were a number of important human factors design issues encountered, like alternative physical spacing of input and output actuators.

Several mechanical engineering design issues are also important, such as isolating multiple vibrations from each other within a small space.

The following future changes are suggested if further development of the prototype is pursued:

Better isolation of vibration within the body. Try different materials to mask and isolate the vibrations better from each other. Variations in durometer, viscoelasticity and mass of the body may have better results. Perhaps attaching the vibrating units with spring steel to act as a kinematic spring for isolating the vibrations may also help.

Wireless Implementation. The devices are connected to each other via cables. Similarly, the power source for the devices is connected to an outlet. Future work might include a wireless implementation.

Smaller size. The circuit board for each device is outside the handheld form factor. Re-designing the circuit board with surface-mount components might allow the circuit board to fit inside the form factor.

Developing a new mobile phone protocol. The cell phone infrastructure might be developed so that the devices use the cell phone protocols. Synchronous mobile voice and tactile communications may be possible with some cooperation from telecommunications providers.

6.3 Some interesting design implementations

Along with these suggestions, alternative routes of design and construction may also be of interest.

6.3.1. Alternate distribution of actuators

There are many diverse hardware arrangements that could have been implemented. For example, we could have settled on using a two-handed display, a device that fit on the wrist like a watch. Similarly, tactile displays distributed over the whole body, as used by Gunther (2000) and Geldard (1967), may be of interest.

6.3.2. Variation of bandwidth and complexity

Another design might vary the number of actuators used. We are curious as to the effect changes in bandwidth due to the addition of actuators for more fingers might have and what new usages will arise. . We expect that the ability to use more fingers will better convey nonverbal information.

Another approach is to vary the dynamic range of the actuators. For example, decreasing the range of the actuators to exhibit 3 levels of vibration (none, middle and high) is possible.

6.3.3. Improved Ergonomics

An investigation into a decreased number of fingers employed may also be of interest. Currently, the fingers are used to position the device and engage the vibration mechanisms. Also, research in ergonomics shows that the fourth and fifth fingers are mechanically coupled. Also, reducing the number of vibrations may be more comfortable, and make it easier to distinguish the vibrations from one another.

6.4 Expanding the design space

As mentioned before, the design chosen was rather specific to the vision of the researchers. The design space for tactile communication is wide open, and other design alternatives are discussed below. A brief listing of "design for the senses" is given to help begin research in each area.

6.4.1. Exploration of other modalities

One of the ongoing themes of this project is how the information should be presented and used by people. The ComTouch implementation focuses on strictly vibrotactile stimuli. The use of vibration for the low level communication has proved popular in communication devices (e.g. pager), but there are issues of ergonomics, robustness, ease of use and cost if the device is to become widely used.

While the sole sense of touch in communication can be effective (Geldard, 1967), the use of touch in combination with other senses reinforces perception and communication. Other types of available stimuli, such as force feedback or thermal feedback, and their effects on remote communication can be further researched. The following list provides a brief overview of research on tactile stimulation in combination with other sensory modalities.

6.4.2. Touch as a sensory substitution to Audio

The current vision is to implement the addition of audio processing into the device. Another approach is to translate the audio channel into vibrotactile stimuli to allow users who are comfortable with audio expression communicate with users who rely on tactile expression. One idea is that people would be able to talk normally to their ComTouch and the receivers would feel vibration from their cell phones.

6.4.3. Touch and Smell

Experiments on smell and memory prove that there is a connection between memory recall and smell (Aggleton 1998). Memories involving smell are more emotional than those involving touch (Herz 1996). Ehrlichman (1998) has used smell to recreate moods. One study found that smells that relate to past experiences could allow adults to recall childhood memories with great accuracy (Aggleton 1999). Kaye (2001) gives a comprehensive overview of applications using smell as an information display. When touch and smell are transmitted in the same communication device, the interaction is more emotional and memorable.

Smell is perhaps the hardest application to work with. Scratch-and-Sniff technology is a fad technology that is no longer popular. After the process of digitizing smell was discovered, companies like DigiScents, AromaJet and France Telecom introduced devices for broadcasting smells in a variety of contexts (for web browsing, game playing and trade-show displays). These companies claim that the addition of smell could combine to enhance interactions by engaging more senses. Unfortunately, the manufacture of smell devices is still too costly for widespread availability. Perhaps a device that transmits the smell and touch of objects relating to past events (such as birthday cake, childhood objects, vacation artifacts) may make people identify and remember the past more vividly.

6.4.4. Touch and Vision

Studies show that combined audio and visual stimulation results in quicker timing of reflexes and better low-level perception in children and animals (Stein 1993). Research on machine learning showed that semantically supporting the visual presentation of an object with a simultaneous spoken reference to an attribute of the object, like its color and shape, led to faster and more accurate word learning (Roy 1997).

Tactile information is also used to reinforce learning by recreating experience. Flight simulators, for example, use a combination of touch and visual displays for training pilots by simulating the physical and visual experience of flying. Perhaps a communication device that integrated touch and vision could combine the benefits of both modalities. A more adaptive and immersive experience may result. For example, such a tactile-enhancement of a navigation system may allow people to maneuver through an unknown area privately and without losing track of a certain reference point, resulting in (by combining tactile and visual direction signals).

6.4.5. Touch Displays

Currently there are two main modes for representing tactile stimuli. One is by means of static contact pressure, and using force feedback to display information. Tactile or pin array displays and force-feedback displays both fall into this category. The second means is by use of vibration signals. Furthermore, for each display, there can be variance in the location of the display, then number of stimuli presented on the display, as well as the duration of the information presented.

6.4.6. Static Displays (General Haptic Displays)

Many early explorations of touch communication used direct representation. Although vibration output is less prone to fatigue than force displays, a central question to this research that should be addressed is that in an ideal world, what would users prefer? Much work in virtual reality is concerned with haptic representation of force on the fingertips. Devices such as the Phantom use force-feedback to simulate the reaction force of pressure exerted from a physical object. Assistive devices, such as the Braille Note use arrays of raised pins to represent Braille letters that can be felt underneath the fingertip. In fingerspelling, the pressure and movement of fingers from one hand on another allows communication.

6.4.7. Vibration Displays

The displays for vibrotactile stimuli can be located anywhere on the body. Distributed multiple stimulations over different areas throughout the body is commonly used. For example, speakers are embedded throughout the body (e.g. wrist, elbows, armpits and lower back) in Gunther's SkinScape (Gunther 2001, Geldard 1970).

In the Tadoma method (Reed 1991), the "listener" places their hand on the speaker's jaw and throat, sensing the vibrations that occur during normal speech. It is possible that these vibrations could be captured and transmitted to a device like the ComTouch so that the listener could be separated from the speaker allowing them to communicate remotely.

The author believes that in an ideal world, if representing touch directly were both technologically and ergonomically feasible, direct mapping of touch would be preferable. However, at this point in time, technology and ergonomic designs have not addressed how to represent the communication of touch in an intuitive manner.

6.5 Summary

This thesis introduced *ComTouch*, the basis for a new class of tactile communication interfaces. The ComTouch device has two unique design features that have contributed to the improvement of touch communication. The main contribution of this work is the novel vibrotactile mapping for transmitting the sense of touch. The secondary contribution is the rationale to use touch as an augmentation to voice communication.

Unlike previous approaches to touch communication, the new design utilizes the distinct and easily understood methods of voice transmission to highlight the subtle and personal qualities of touch. By examining the correlation between the touch and audio modalities, it was much easier to discern the usage of the tactile channel. The use of tactile information as an augmentation to voice provides a good way to highlight the unique qualities of communication inherent in both modalities.

The ability to correlate this new tactile channel to the more thoroughly researched channel of audio communication allowed better focus of the use of touch. User studies illustrated that nonverbal qualities of tactile communication correlate in meaningful way to the voice channel, as shown by the discovery of the three tactile gestures: emphasis, turn-taking and mimicry. By examining the use of touch in contrast to existing modes of communication, we have begun discussion of the architecture of a touch language for remote communication.

This thesis presents the use of vibrotactile transducers to enable touch communication into handheld and small devices, thus enabling a new type of device design in the field of mobile tactile communication. The series of iterative design implementations have revealed new uses of vibration actuators. This new application for vibration transducers allows users to convey nonverbal physical information in a more private manner, thus enhancing audio communication. It is hoped that the research presented in this thesis will motivate the development of a new class of interpersonal mobile communication devices that truly do allow us to 'keep in touch' with one another.

Appendix A Part Resources and Electrical Diagrams

Below is a brief skeleton on how to build a vibrotactile channel. I used standard components for the schematic, so will only mention where to find vendors for unusual parts.

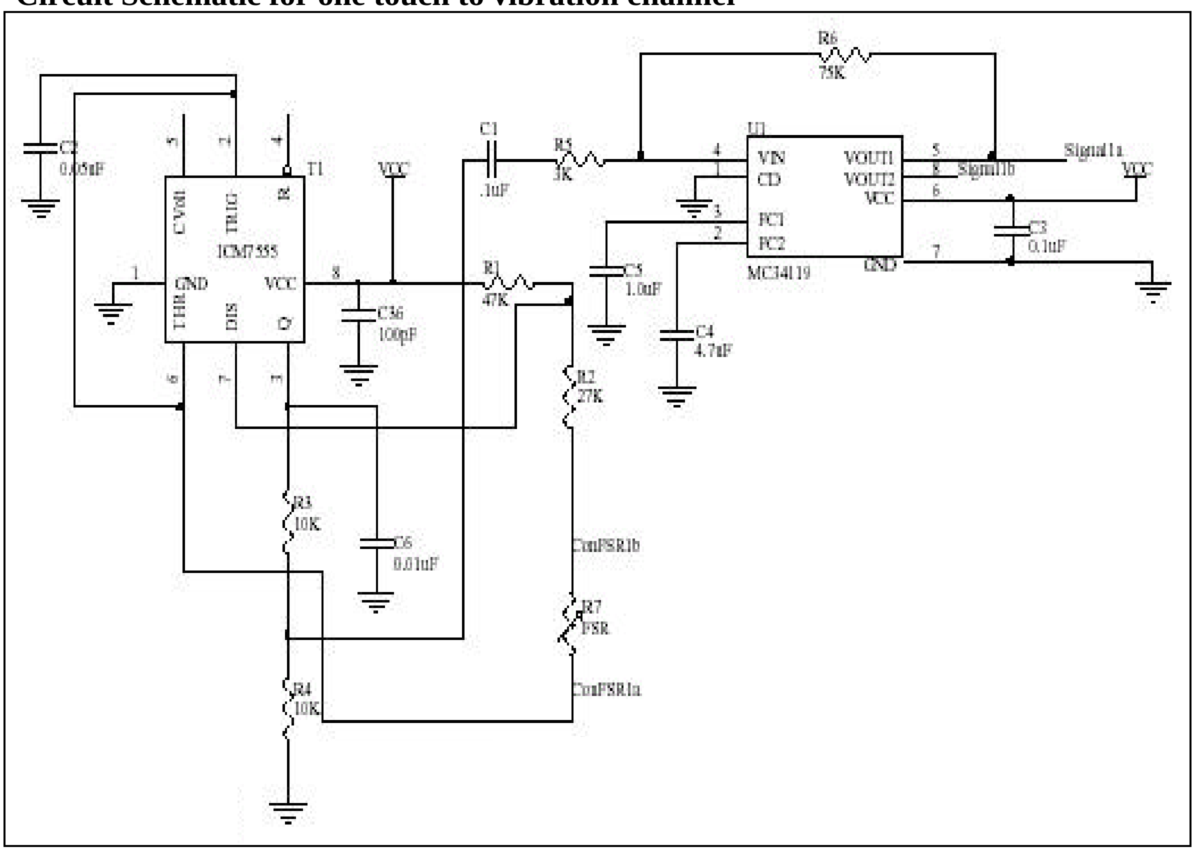
Electronic Parts Vendors for Nonstandard Parts
Active Electronics
http://www.future-active.com

AudioLogic Engineering (Dave Franklin)
http://www.tactilator.com/audiologicalengineering/

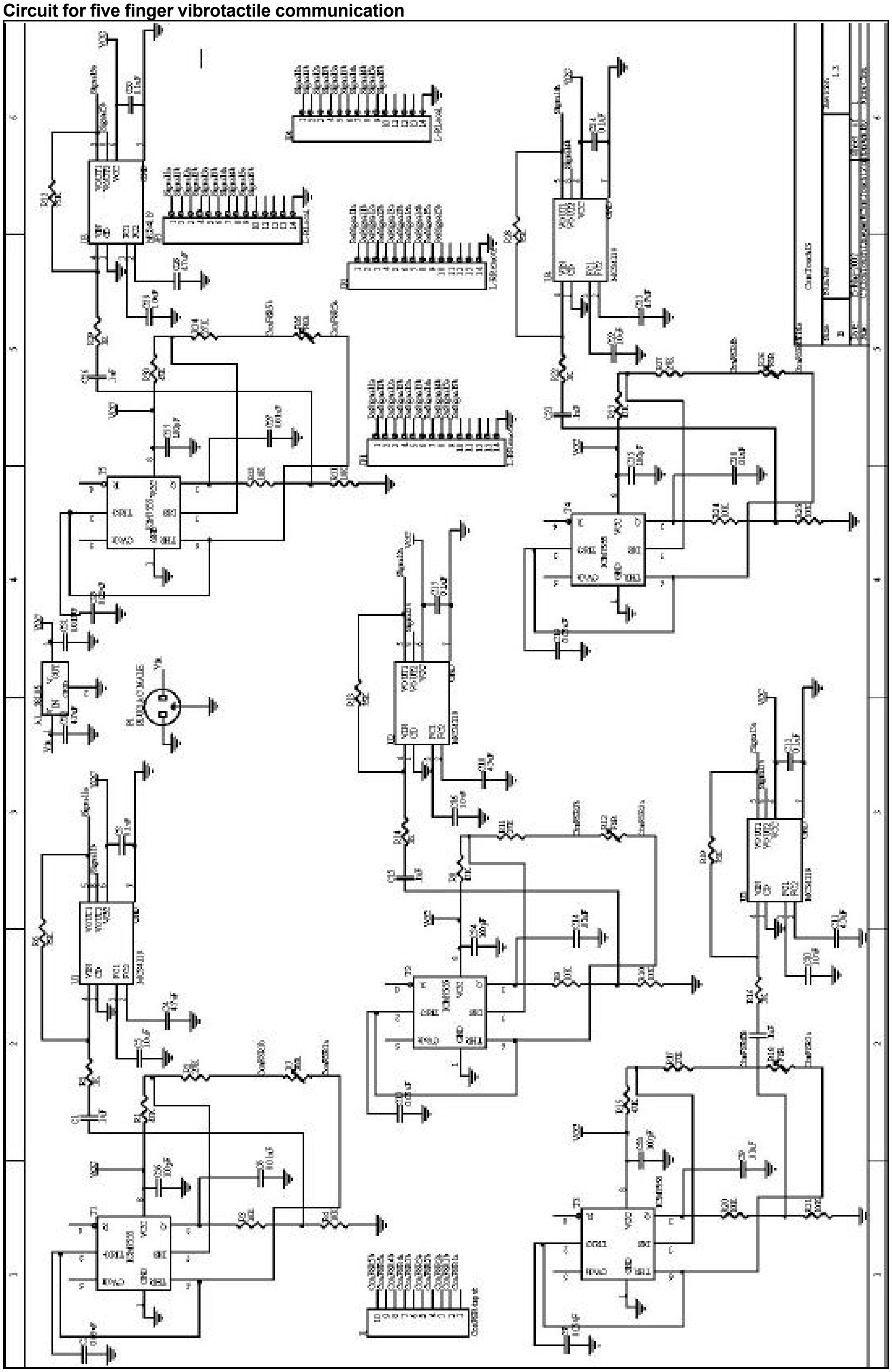
Interlink Electronics
http://www.interlinkelec.com

Description	Part No.	Online	Vendor
Speaker Transducers for producing vibration	V1220	Audiologic engineering	Audiologic engineering
low-Power audio amplifier	MC34119P	Active Electronics	Motorola
Force Sensing Resistors	FSR	Interlink Electronics	Interlink Electronics

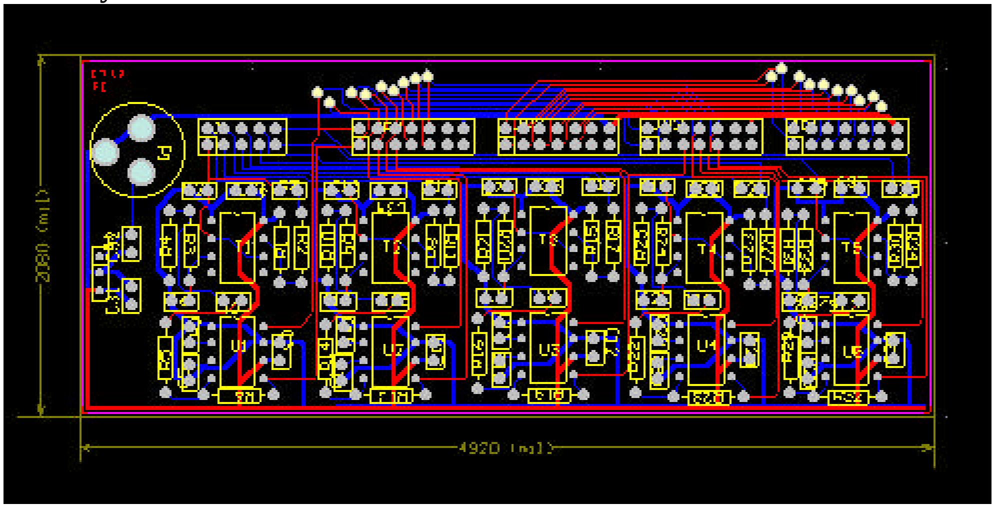
Circuit Schematic for one touch to vibration channel



Circuit for five finger vibrotactile communication



PCB layout



Appendix B Testing Materials used in Experiment

(Total time ~ less than 1 hour)

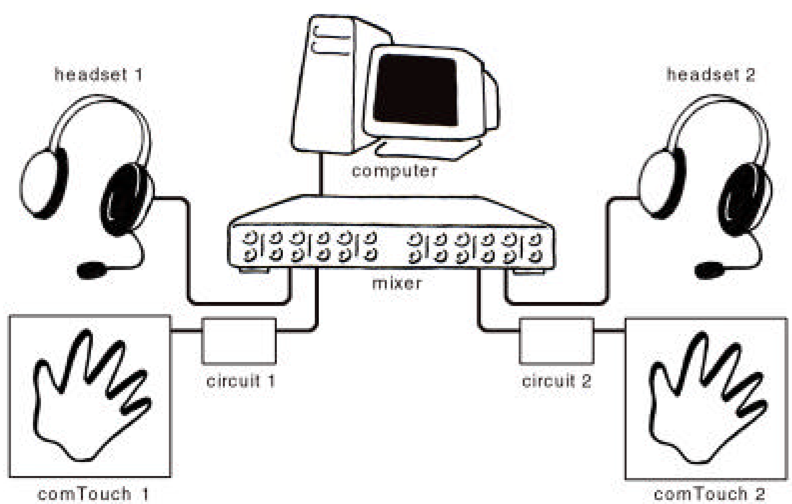
Experiment Materials List:	Approximate time to spend on each material
• Experimenter's Script	(~7 minutes)
• Informed Consent Form	(~1 minutes)
• Preliminary Questionnaire	(~5 minutes)
• Tactile Introduction Task Sheet	(~5 minutes)
• Desert Scenario Task I	(~5 minute)
• Desert Scenario Task II	(~15 minutes)
• Exit Questionnaire	(~10 minutes)
• Payment vouchers for participants	(~2 minutes)

Experiment Equipment List:

- 2 ComTouch Pads with circuits
- 2 Headsets with Microphones
- 1 DIGI001 Box (hardware interface)
- 1 Macintosh G4 computer for storing data.
- 1 MAX MSP Software for data acquisition of four simultaneous signals.

Analysis Software package

- 1 Sonic Foundry Acid™ Software for analysis, or a similar program that allows simultaneous graphing and replay of four audio signals.



B-1. Experiment setup and apparatus

Experimenter's Script

Welcome and thank you for coming to participate in the study. The purpose of this study is to observe vibrotactile communication. First please fill out the subject consent form.

- {Give participants Subject Consent Form}

This device here {point to ComTouch} allows you to send your squeeze pressure to your partner in the form of vibration. We will give you a few tasks and record your audio and vibrotactile exchanges. The experiment consists of both questionnaires and using a small vibrotactile device to complete a negotiation task. Each of you will feel small vibrations under each finger during the experiment. If at any time you feel uncomfortable or have a question, please ask. First, please fill out this preliminary questionnaire.

- {Give participants Preliminary Questionnaire.}

Now please put on the earphones, and place your hands on the pad. The ComTouch is a vibrotactile device that allows tactile communication. The device translates squeeze pressure under the forefinger to vibration. When you press down with the tip of your finger on the yellow pad, you can feel vibration related to the pressure of squeezing on the green pad at the middle of your finger. The harder you squeeze, the harder the vibrations. The softer you squeeze, the slower and softer the vibrations. The vibrations are also transmitted so that the squeeze can also be sent to your partner, who can feel your squeeze under the base of the finger on the blue pad. The device is bi-directional, and you can also feel your partner's squeezes. Both of you can squeeze at the same time.

Now, can you both feel the vibration under each finger? Can you feel your partner's vibration?

Now pick up the microphone, can you hear the other person?

- {Give participants Tactile Introduction Task Sheet.}

Are there any questions? Is anyone uncomfortable with the task?

Now we move on to the experiment itself. The name of this task is called the desert survival scenario. I will first read out the scenario and then give you 5 minutes to do the task.

- {Give participants Desert Survival Task Sheet.}

Now, please set aside the sheet of paper with your individual rankings.

- {Give participants Team Desert Survival Task Sheet.}

Now, please use the ComTouch in your conversation. We are recording both the audio and tactile data.

- {Start monitoring experiment. If necessary, give them the Quiet sign.}

Now it is time for us to finish up the experiment with an exit interview. Please read and answer the following questions.

- {Give exit questionnaire.}

Now here is your copy of the consent form and the payment voucher.

- {Give payment voucher.}

Thank you for participating!

Preliminary Questionnaire

Write your initials________ today's date_________

Please circle the most appropriate answer:

Your age range:

Your sex: M F

Do you have any known problem with your hands, such as carpal tunnel or sore fingers? Y N

Do you describe yourself as left-handed or right-handed?

Did you know your partner before this experiment? On a scale of 1 to 5, rate how well you know them. Circle one below:

1= best friends

2= good friends

3= friends

4= know slightly

5= stranger

How comfortable would you feel touching the other person's hand? Circle one below:

1= very comfortable

2= comfortable

3= no opinion

4= uncomfortable

5= very uncomfortable

Tactile device introduction task

Please spend 5 minutes familiarizing with the device by using it in conversation. Talk about any of the following topics (choose one):

Something you did last weekend
Next weekends plans
Homework
A movie you recently saw

INDIVIDUAL TASK – 5 minutes

Individually rank each item. Do NOT discuss the situation or problem until each member has finished the individual ranking. Fill out the form for the individual ranking. Your task is to rank these items according to their importance to your survival, starting with '1' the most important, to '15' the least important.

	Rank
large flashlight & batteries	________
jackknife	________
sectional air map of area	________
large plastic raincoat	________
magnetic compass	________
first aid kit with gauze	________
loaded .45 caliber pistol	________
red & white parachute	________
bottle (1000) salt tablets	________
2 liters of water	________
book: Animals of the Desert	________
1 pair sunglasses per person	________
2 liters 180- proof Vodka	________
1 large coat per person	________
a cosmetic mirror	________

TEAM TASK – 15 minutes

After each person has finished the ranking, you discover that there is only one knapsack (the other one has a huge hole) and that between the two of you, and can only carry only five things in the knapsack. As a team, discuss which 5 things you should bring together. Once team discussion begins, do not change your individual rankings.

As it turns out, enemy observers are in the area and can overhear your conversation. The enemy has not yet located your position, but has the technology to locate your position based on sound. Please be discrete about talking, and try not to talk too much. If you are in danger of being found due to too much noise, the experimenter will notify you by presenting a card that says

"Quiet, enemy patrols in the area."

Time is of the essence, as you only have 10 minutes before the enemy patrols find your ship. Please make sure that you agree on the items and their rank of importance.

	Rank
large flashlight & batteries	__________
jackknife	__________
sectional air map of area	__________
large plastic raincoat	__________
magnetic compass	__________
compress kit with gauze	__________
loaded .45 caliber pistol	__________
red & white parachute	__________
bottle (1000) salt tablets	__________
2 liters of water	__________
book: Animals of the Desert	__________
1 pair sunglasses per person	__________
2 liters 180- proof Vodka	__________
1 topcoat per person	__________
a cosmetic mirror	__________

Quiet,
enemy patrols in the area

Exit Questionnaire- 10 minutes

What was difference between your individual ordering and the team ordering?

Which items did you each end up bringing as a team?

Did you reach an agreement on which 5 items to bring?

Did you agree on an ordering?

What was the agreed-upon ordering?

How do you feel about using the device to communicate? Did it help at all?

What method did you use to communicate using the tactile channel?

Rate how difficult this task was on a scale of 1(easy) to 7(hard)?

Do you think this technology could be useful, to augment phone conversations, for example?

Do you have any feedback on the device or the experiment?

Other comments?

Informed Consent Form
Experiment Title:
An investigation of the information content and effect of the vibrotactile channel
Principle Investigator Angela Chang
Research Assistant * MIT Media Lab * Tangible Media Group * 1 Cambridge Center * anjchang@media.mit.edu

Subject #: _______ Date:_______

Participation in this experiment is fully voluntary and I am aware that I am free to withdraw my consent and discontinue participation at any time without prejudice to myself. I will be paid $10 / hour and this will be prorated for early withdrawal. The experiment lasts less an hour, and I may be asked to participate in other experiments at later time.

Experiment overview

This series of experiments has been designed to obtain quantitative and qualitative data on the use of a handheld vibrotactile device, using small vibrations under each finger. A series of small vibrations will be presented under my right hand and I will be asked about the comfort level. The experimenter will adjust different parameters until comfort is achieved. I will be asked to perform tasks and provide a qualitative account of the experiment.

The sensations produced by the apparatus might feel “strange”, but at no point in the experiment should these sensations cause any discomfort. The sensations are very similar to the vibration of a speaker grille. I understand that I may withdraw from these studies at any time for any reason. I confirm that I have passed my eighteenth birthday, the required minimum age necessary to take part in an adult research study.

I consent to the release of scientific data resulting from my participation in this study to the Principal Investigator for use by her for scientific purposes. The Principal Investigator assures my anonymity. I understand that the record of this experiment becomes part of the experimental results and is protected as a confidential document. I understand that this record will only be available to the investigators involved with this study. Other staff may be authorized by the COUHES board to review the record for administrative purposes or for monitoring the quality of subject care.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid, emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the fault of the Investigator(s). I also understand that by my participation in this study I am not waiving any of my legal rights*.

I understand that at any point before, during, or after the experiment, I can direct any inquiries concerning the experiment to Angela Chang (anjchang@media.mit.edu, 617-452-5618).

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects (COUHES) Secretary, MIT E23-230, 253-6787, if I feel I have been treated unfairly as a subject.

I have read and fully understand all of the above points.

Signature:_______________________________________ Date:______________________

Witness:____ Date:______________________

* Further information may be obtained by calling the Massachusetts Institute of Technology's Insurance and Legal Affairs Officer at 253-2822.

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