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Perception of Small Device Vibration Characteristics - Test Facilities Setup and Study

Master's Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology.

Helsinki, October 12, 2004

Supervisor: Professor Iiro Jääskeläinen

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HELSINKI UNIVERSITY OF TECHNOLOGY	ABSTRACT OF THE MASTER'S THESIS

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Artificial vibrations can be produced, for example, with an eccentric vibration motor that is inserted inside a small device like a mobile phone. This thesis discusses the theory of perception of such vibration stimuli, in addition to the perception of multi-modal stimuli like vibration and an auditory stimulus at the same time.

Experiments were conducted on existing vibration measurement facilities that were moved to a new location. A method for creating stimuli was introduced and a series of these was measured. The same stimuli that were measured were also used in a user test conducted on perception of synchronous tactile and auditory stimuli.

Eleven stimulus pairs were created, each one with a 100 ms symmetric vibration stimulus and a temporally varying auditory stimulus. The stimuli were generated using a stimulus-producing device that allows output of multiple voltages. For the user tests, a user interface was created with Python programming language, allowing the device to be controlled while simultaneously collecting answers from the users.

The measurements showed that a symmetric vibration stimulus was successfully achieved. The results of the user tests indicate that the perception of multi-modal stimuli varies greatly, at least under the test conditions used in this thesis. The temporal range of perceived synchronism between tactile and auditory stimuli is relatively wide, but vibration was detected earlier than had been assumed. The temporal center point of perceived synchronism turned out to be before the middle of the vibration stimulus.

Keywords: vibration perception, sensory integration, mobile context, ergonomics, tactile interfaces, multi-modality, haptics, sense of touch, user experience, user tests

TEKNILLINEN KORKEAKOULU		DIPLOMITYÖN TIIVISTELMÄ
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Keinotekoista värinää voidaan tuottaa esimerkiksi pienen laitteen, kuten matkapuhelimen, sisälle laitettavalla epäkeskolla värinämoottorilla. Tässä diplomityössä esitellään sekä kyseisenlaisten värinä-ärsykkeiden että multimodaalisten ärsykkeiden havaitsemisen teoriaa. Multimodaalisia ärsykkeitä ovat esimerkiksi samanaikainen värinä ja ääniärsyke. Jo olemassaolevat värinän mittaukseen tarkoitetut laitteet siirrettiin uuteen paikkaan, ja niillä tehtiin kokeiluja. Työssä kehitettiin tapa, jolla ärsykkeitä voitiin luoda, ja ärsykesarja mitattiin. Samoja ärsykkeitä käytettiin myös käyttäjätestissä, jossa tutkittiin tunto- ja ääniärsykkeiden samanaikaisuuden havaitsemista.

Työssä tehtiin yksitoista ärsykeparia. Jokaisessa ärsykeparissa oli 100 ms tasasuhtainen värinä-ärsyke sekä ajallisesti vaihteleva ääniärsyke. Ärsykkeet luotiin laitteella, jolla voidaan tuottaa useita jännitteitä eri kanaviin. Käyttäjätestejä varten ohjelmoitiin Python-ohjelmointikielellä käyttöliittymä, jolla voitiin sekä ohjata laitetta että kerätä käyttäjiltä vastaukset.

Mittaukset osoittivat, että tasasuhtaisen värinä-ärsykkeen luomisessa onnistuttiin. Käyttäjätestien tulosten mukaan multimodaalisten ärsykkeiden havaitseminen vaihtelee paljon, ainakin tässä työssä käytetyssä testitilanteessa. Havaitun samanaikaisuuden alue aikatasossa tunto- ja ääniärsykkeillä on melko leveä, mutta värinä havaittiin oletettua aikaisemmin. Havaitun samanaikaisuuden ajallinen keskipiste oli ennen värinä-ärsykkeen keskikohtaa.

Avainsanat: värinän havaitseminen, sensorinen integraatio, liikkuvuuskonteksti, ergonomia, tuntokäyttöliittymät, multimodaalisuus, haptiikka, tuntoaisti, käyttäjäkokemus, käyttäjätestit

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Timo Jyrinki

Contents

Abbreviations

ALS	Anterolateral system
ANS	Autonomic nervous system
BASIC	Beginners All-Purpose Symbolic Instruction Code
BS	BASIC Stamp
CNS	Central nervous system
CSV	Comma Separated Values
CVS	Concurrent Versions System
DC	Direct current
DCMLS	Dorsal column medial lemniscal system
DIP	Dual In-line Package (electronic device package)
EEPROM	Electrically-Erasable Programmable Read-Only Memory
EPS	Encapsulated PostScript
GNU	GNU's Not UNIX
GPS	Global Positioning System
GUI	Graphical User Interface
HCI	Human-computer interaction
IC	Integrated Circuit
ISO	International Organization for Standardization

IT	Inferotemporal
KDE	K Desktop Environment
LaTeX	A document preparation system for the TeX typesetting program
LED	Light Emitting Diode
LGN	Lateral geniculate nucleus
MRI	Magnetic Resonance Imaging
MT	Mediotemporal
PC	Personal Computer
PCMCIA	Personal Computer Memory Card International Association
PDA	Personal Digital Assistant
PNS	Peripheral nervous system
PWM	Pulse Width Modulation
RA	Rapidly adapting
RAM	Random Access Memory
RS	Recommended Standard
SA	Slowly adapting
UI	User Interface
UNIX	UNiplexed Information and Computing Service
USB	Universal Serial Bus
Vx	Visual area x (e.g. V1)

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Chapter 1

Introduction

Current multi-modal (multi-sense) technologies usually involve using two modalities at the same time for interacting with the device. For example, Personal Digital Assistants (PDAs) may use both vision (the display) and the sense of touch (vibration from a touch screen or the pen used to control the device) for outputting information to the user, while acquiring information via different input methods like the pen and voice recognition. It is more often than not that "true" multi-modality is not used - various input methods may be present, but they are not used at the same time.

Telecommunication may become more involving with proper implementation of multi-modal input and output methods in the future. Producing artificial vibrations and studying perception of these is one way to include the sense of touch in the senses that are used when interacting with small devices like mobile phones.

1.1 Background

This thesis discusses mainly the sense of touch, but for understanding the co-operation of different senses (i.e. multi-modality), other senses need to be studied as well. Auditory and cutaneous stimuli will be used in this thesis, so hearing will also be covered here, if briefly. Vision is covered to shed some light on how different the processing of different stimuli is. Vision is also often regarded as the most important sense. The aim of this section is to examine the theory of sensations in general (going deeper into the sense of touch and vibrations), to examine how that information is integrated with other senses, and finally to explore the concepts of haptics and vibration.

1.1.1 Sensations

The sense of touch is one of the five sensations (touch, vision, taste, smell and hearing) than can be directly related to specific sensory organs (skin, eyes, mouth, nose and ears) (McLinden & McCall, 2002). Other receptors include those that provide vestibular (balance), proprioceptive (body space and position) and homeostatic (body temperature) information. As for multi-modal applications, usually vision, hearing and touch or any combination of these are considered.

A sense organ is a tissue system sensitive to energies applied from both the environment and also from within the body. Each of the sensory organs contains nerve cells or sensory receptors that are designed to turn sensory information into electrical activity. This electric information travels through the nervous system and finally transmitted to the appropriate areas in the brain.

Central Nervous System

Central nervous system (CNS) receives sensation information from the peripheral nervous system (PNS) and autonomic nervous system (ANS) and processes it. CNS also sends orders to muscles and endocrine glands (Ilmoniemi, 2001). CNS consists of cerebrum, cerebellum, brain stem (*truncus cerebri*) and spinal cord (*medulla spinalis*). Cerebrum, cerebellum and brain stem are what is generally recognized as "the brain".

Cerebrum consists of two hemispheres, which are divided into four lobes - they are the frontal lobe (*lobus frontalis*), parietal lobe (*lobus parientalis*), occipital lobe (*lobus occipitalis*) and temporal lobe (*lobus temporalis*). The outer layer of each hemisphere is referred to as the cortex.

Different senses transmit the sense information primarily to specific areas of the brain. In the Figure 1.1 these areas are shown for senses of vision, hearing and touch (somatosensory cortex includes also processing of proprioceptive information). The figure also shows most of the CNS with the exception that only a part of the spinal cord is shown.

Vision and hearing are the most studied senses of the human senses. For vision, eyes are the sensory organs and for hearing, ears are the sensory organs. Both have a relatively short path in the cortex, but the actual locations for processing sensory information are not in the immediate vicinity of the organs. Regarding the sense of touch and multi-modality examined later, the visual and auditory pathways should be mentioned. Auditory stimuli will be used in the measurements and the user tests later on.

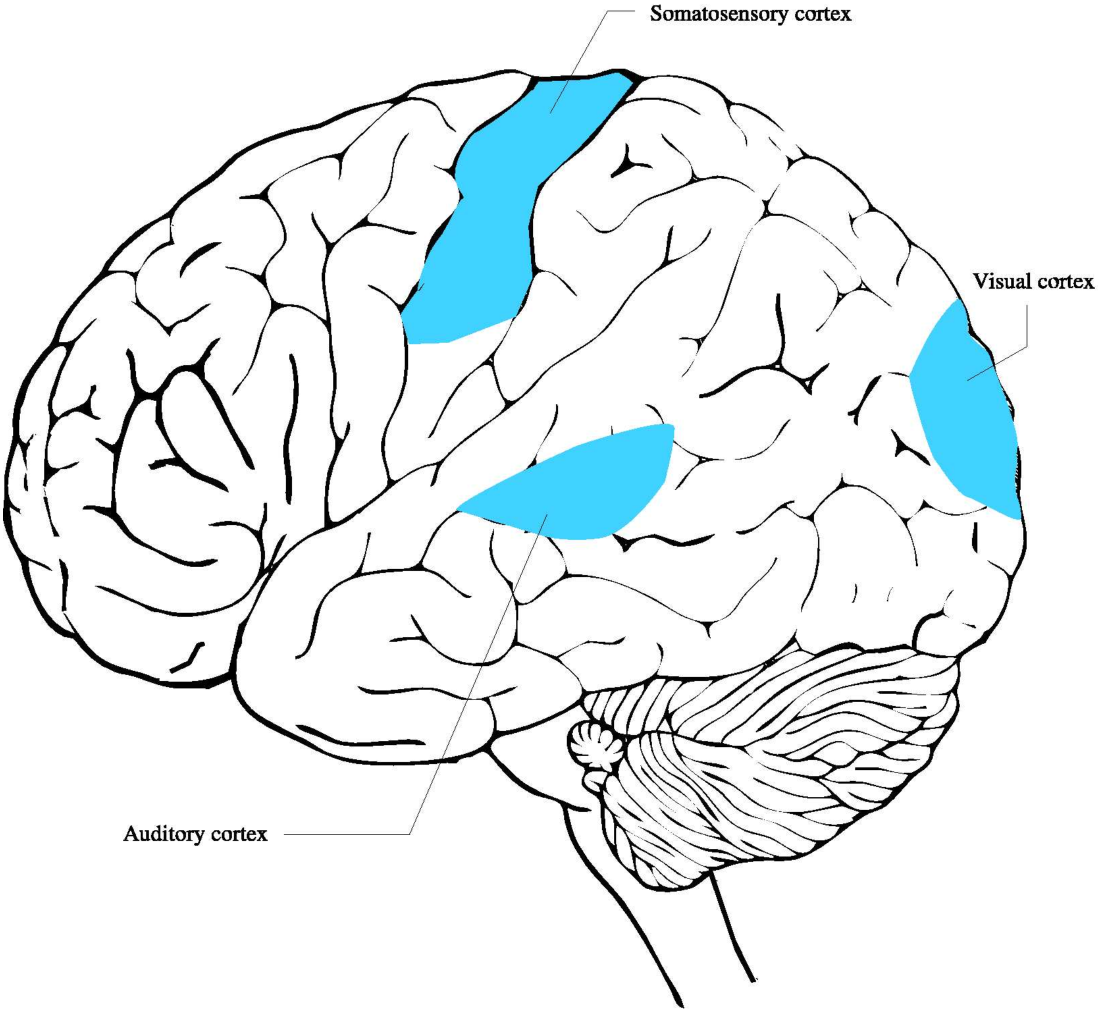

Figure 1.1: Diagram of the human brain, showing the main sensory receiving areas. (modified from Goldstein, 2001)

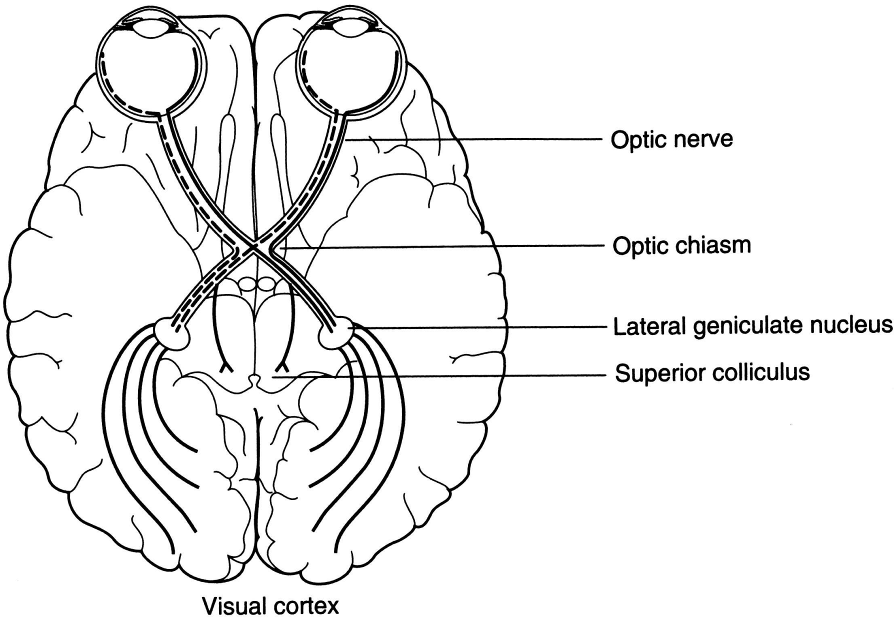

Figure 1.2: Diagram of the visual pathway from the eye to the visual cortex. (Goldstein, 2001)

Vision

In addition to the eyes, the most important areas of the visual system are the lateral geniculate nucleus (LGN) in the thalamus and the primary visual cortex in the occipital lobe. These are presented in the Figure 1.2. The primary visual cortex is also known as the striate cortex, because of the white stripes created by nerve fibers that run through it. The white stripes were first spotted already in 1776 by Francesco Gennari, and only over a century later did Salomen Eberhard Henschen find out that the cortex with the prominent stripe is the primary visual center of the brain (Glickstein, 1988).

An eye and the LGN are connected via optic nerve, and the optic nerves from each eye cross in optic chiasm on their way to LGN or, in case of about 10% of the signals, to superior colliculus. The part of the nerve between optic chiasm and LGN is called tractus opticus (Ilmoniemi, 2001). From LGN, the signals continue their journey to the striate cortex via optic radiation. However, it is noticeable that the LGN actually receives more input back from the cortex than it receives from the retina (Sherman & Koch, 1986).

The visual processing on the visual cortex starts at the primary visual cortex (V1).

Simplifying the route information processing takes from there, the information first proceeds to V2. From there, it's generally thought that the information related to *where* will go to a parietal pathway, i.e. V3 and MT (mediotemporal cortex), and information related to *what* will go to a temporal pathway, i.e. V4 and IT (inferotemporal cortex) (Ungerleider & Haxby, 1994). However, simplifying the visual information processing this much loses many details. Not only the mentioned separate pathways already begin in the eyes, in the M-ganglion and P-ganglion cells, but there are also many kinds of connections to other parts of the cortex and many feedback and feed-forward connections going either back to an "earlier" part of the visual pathway or skipping some parts of it.

Hearing

The auditory pathway begins in the ear. Sounds travel through the outer ear to the cochlea in the inner ear, where the hair cells in the organ of Corti transform the sound to electrical signals. The auditory nerve carries the signals generated by the inner hair cells away from the cochlea and toward the primary auditory cortex. This is illustrated in Figure 1.3. During the auditory pathway audio signals are processed in many ways. Much processing happens already in the inner ear, where for example different sound frequencies are summed and adaptation occurs according to the sound pressure experienced.

A person hearing something from a distance hears the sound after for example seeing something or feeling something. This is because the speed of sound is only about 340 $\frac{m}{s}$ in free air. Thus, it's more natural that the auditory event is a bit late than if it was sensed earlier. There's also a delay, like with any sense, in the perception of sound. The delay consists of signal traveling in the brain and the processing of the stimulus. The delay in processing can be seen in, for example, the *pre-masking* effect, which means that a sound stimulus at a given time can mask another (slightly more quiet) sound that happens before the louder stimulus (i.e. masking noise). Masking is one of the many psychoacoustical concepts studied. Temporal pre-masking happens effectively only about 5-10 milliseconds before the masking noise, but post-masking affects 150-200 milliseconds after the masking noise (Karjalainen, 1999). This "twist of causality" (in the case of pre-masking), or the result of the complex auditory processing being not instantaneous, is used in for example audio compression technologies that utilize psychoacoustics (Painter & Spanias, 1997). These kinds of delays and ways of processing might also have an effect on how a person perceives synchronous tactile and auditory stimuli, because

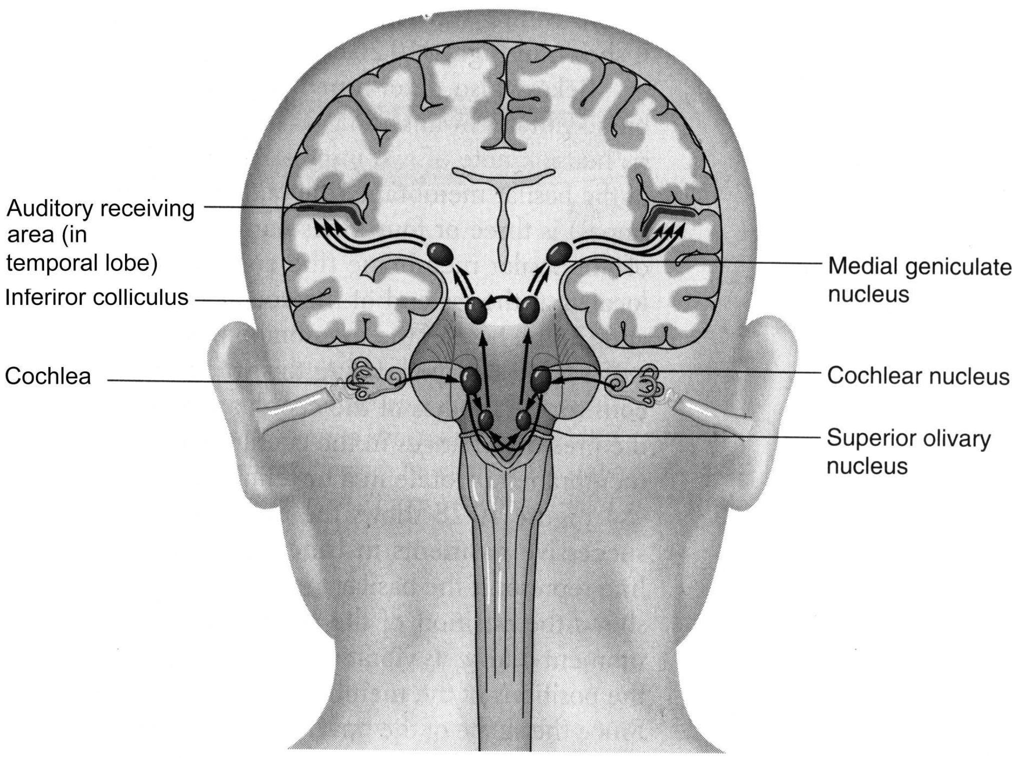

Figure 1.3: Diagram of the auditory pathway after the sound is converted to electric signals in cochlea. (Goldstein, 2001)

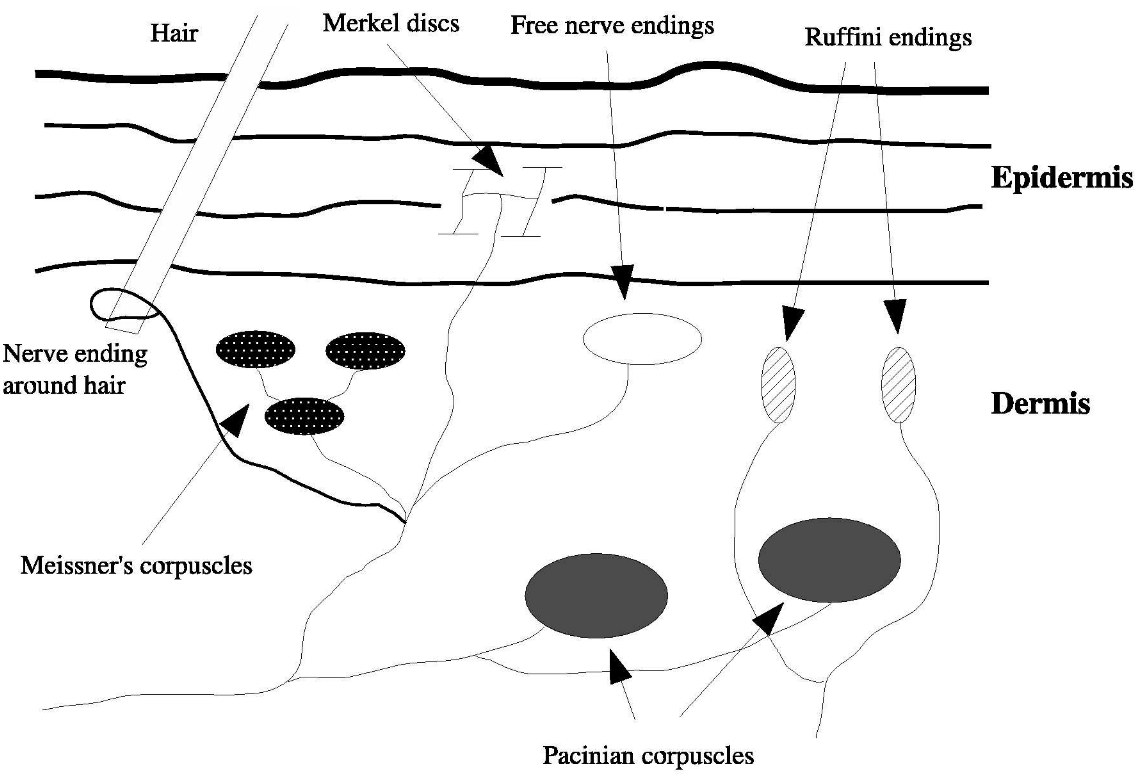

Figure 1.4: Diagram of a cross-section of human skin.

they are processed in different ways.

1.1.2 Sense of Touch

Skin is the sensory organ of touch, and it is the largest organ in the human body. Skin functions as a sensory organ, a protector for the internal organs and a waterproof membrane for the body. It is a part of the PNS.

The skin is made up of two main layers, epidermis and dermis. Epidermis (or outer layer) consists of flattened cells that are constantly replaced from the inside. Dermis (or inner layer) contains hair follicles, sebaceous glands, sweat glands, blood vessels and nerve endings. The nerve endings can be categorized into two main types: free nerve endings, and nerve endings incorporated within another structure (McLinden & McCall, 2002). Examples of the latter ones include Pacinian corpuscles and Merkel's disks.

The nerve endings are commonly classified according to how they react to stimuli. Mechanoreceptors respond to indentations of the skin, and can be further categorized in the group of rapidly adapting (RA) and slowly adapting (SA) mechanoreceptors

(Goldstein, 2001). Thermoreceptors respond to temperatures or changes in temperature, and noiceptors respond to stimuli which damage the skin (for example, intense heat or strong pressure).

SA mechanoreceptors include Merkel's disks and Ruffini endings. Meissner's corpuscles and Pacinian corpuscles are classified as RA. Figure 1.4 is a generalization that illustrates the locations of these structures in relation to one another. Depending on the part of the skin being examined, the number and types of these structures vary considerably (Heller & Schiff, 1991). For example, there are no hair follicles in glabrous skin (like in the skin of the palm of a hand) or Pacinian corpuscles in the skin of the cheek.

It has been shown (Bolanowski *et al.* , 1988) that each type of mechanoreceptor responds best to a specific range of frequencies of mechanical stimulation. According to Bolanowski, the mechanoreceptors respond to frequencies ranging from 0.3 Hz to (at least) over 500 Hz. Each mechanoreceptor is associated with a particular type of tactile perception - Pacinian corpuscles respond to high frequencies and are associated with the perception of vibration.

Processing Pathways

Nerve impulses from receptors in the skin travel in the PNS and enter the spinal cord through the dorsal root. Once they enter the spinal cord, the nerve fibers go up the spinal cord in two major pathways: dorsal column medial lemniscal system (DCMLS) and anterolateral system (ALS). ALS is also called spinothalamic pathway in some literature (Goldstein, 2001). DCMLS carries large fibers that carry tactile (vibration, pressure) and proprioceptive information (positions of the limbs). ALS carries temperature and pain information, and can thus be described as the "survival" pathway. DCMLS is the pathway that carries the vibration information, which is relevant to this thesis.

Fibers from both pathways cross over to the other side of the body during their journey to the thalamus, which is similar to what happens in visual and auditory pathways. Most of the fibers synapse in the *ventral posterior nucleus* in the thalamus. Some also synapse in other thalamic nuclei, and some even in the limbic system (Goold & Hummell, 1993). It must be pointed out that fibers from retina synapse in the lateral geniculate nucleus in the thalamus, and fibers from cochlea synapse in the medial geniculate nucleus. The thalamus is where the information from different senses meet and it forms the basis for multi-modal perception.

From the thalamus, signals travel to primary somatosensory receiving area (S1) in the parietal lobe of the cortex and finally to the secondary somatosensory cortex (S2). Research has shown that there are maps of the body on the cortex, and more area is devoted to the parts of the body that are more sensitive. This is similar to the magnification factor seen in the visual cortex to achieve good detail vision in the central part of the field of vision. This is often illustrated by the *sensory homunculus* shown in Figure 1.5. Earlier, the term homunculus was usually used to describe a “little man” that is running some system or is in the core of a human being (Wikipedia, 2004), but nowadays it has found usage in this distorted human figure.

1.1.3 Multi-modal Perception

Multi-modal perception means perceiving sensory information via multiple senses at the same time. Sensory integration and sensory modulation are used to combine the information into a complete sensation about the environment. Multi-modal technologies utilize multi-modal perception capabilities of a human being to achieve better human-computer interaction (HCI).

Sensory Integration and Sensory Modulation

Sensory integration within the CNS integrates inter-sensory information, wherein information from multiple sources converges onto a neuron or group of neurons. The term also reflects behavior, meaning that the neurological process is used to make decisions on how to use one’s body to effectively interact with the environment (Bundy *et al.* , 2002).

Sensory modulation is needed to filter out sensations, attending to those that are relevant. One needs to be aware of the environment, and at the same time maintain attention to the task at hand. If this part of the sensory integration is inadequate, attention may be too easily diverted to ongoing changes in the sensory environment.

Sensory integration affects how human perceives the multi-modal environment. There are many places in the brain where sensory information is being combined. The *association areas* do just this and also make preparations for motor action based on this information. Main association areas include prefrontal, parietal-temporal and limbic areas (Ilmoniemi, 2001). Combining of sensory information also happens in thalamus (where the LGN resides), through which almost all sensory information (except for olfactory) goes, and in the cortex of cerebellum (*cerebellar cortex*).

Multi-modal research has been of increasing interest lately. In *Neural Synergy Between Kinetic Vision and Touch* (Blake *et al.* , 2004), the authors state that

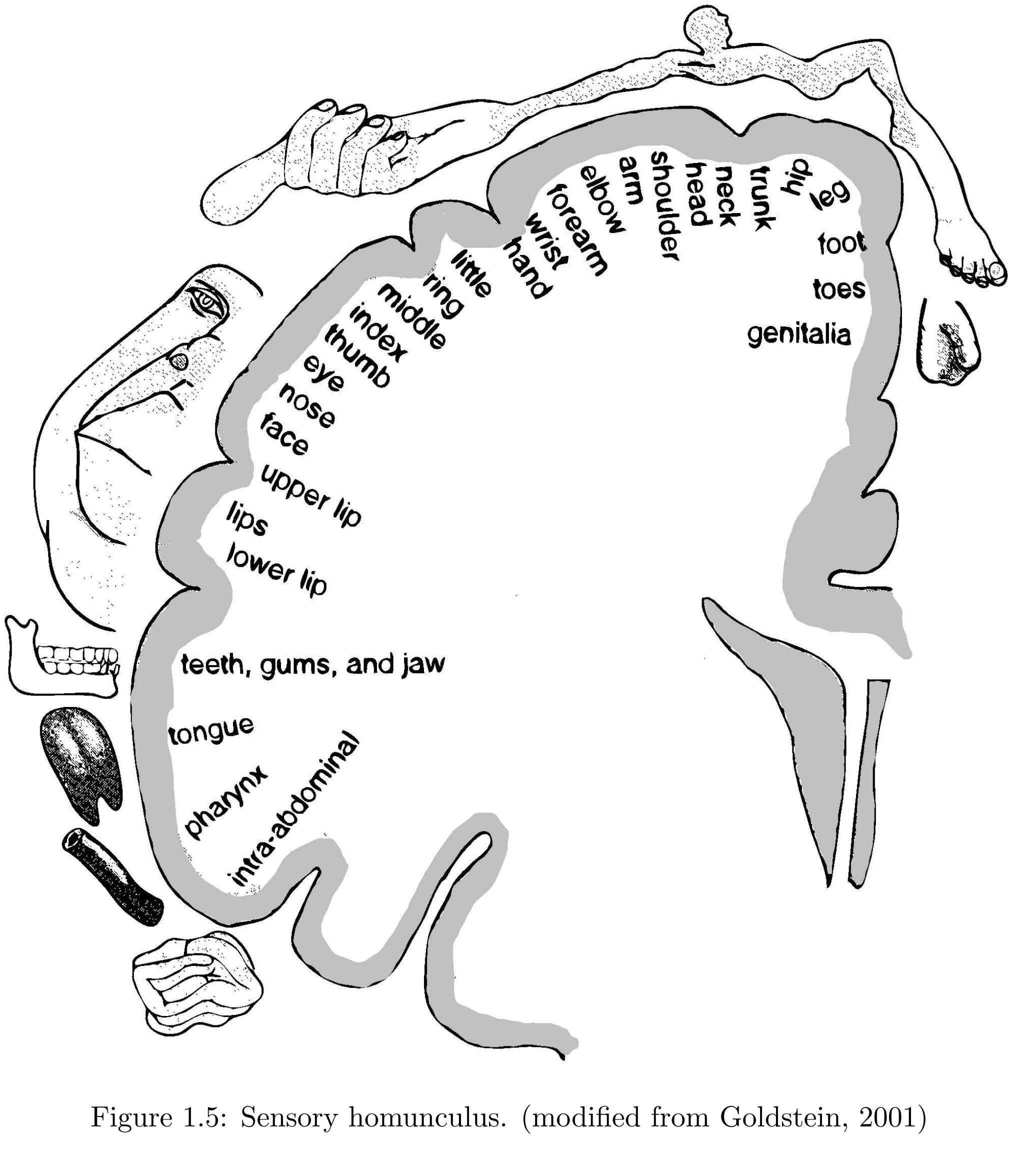

Figure 1.5: Sensory homunculus. (modified from Goldstein, 2001)

somatosensory information helps to resolve visual conflicts. In their study they found that tactile information about the direction of rotation of a globe with ambiguous three-dimensional structure influences the visual perception of the globe. They also used magnetic resonance imaging (MRI) to discover that touching the rotating globe (even without looking) activated the MT visual complex, which is a part of the visual pathway.

McGurk effect is a fairly well-known early study about bimodal perception. In the study, subjects were shown a video clip of someone saying */ga/*, while the subjects were made to hear someone say */ba/* at the same time. As a result of this mix-up, most subjects actually "heard" */da/* (McGurk & MacDonald, 1976)! This is an example of how bimodal sensations are integrated.

Multi-modal perception in the human brain is a very complex subject, so thorough understanding of it will be a very difficult challenge for the future. Findings about multi-modal perception are fairly specific and are often not supplied with the information *why* something is perceived like it is. Unlike with multi-modal perception, many parts of for example visual and auditory information processing have been covered in much detail. Those studies consider the senses separately. A study about a single sense does give information that may also be applied when designing user interfaces (UIs), like in the case of how a person reads text or perceives images when he/she enters a web page on the Internet. However, this information doesn't really help designing *multi-modal UIs*, which is why the development of such an UI is not a trivial task.

Mobile context

Real life is a multi-modal experience, so interfacing with small devices like mobile phones can be made more interesting and natural by utilizing multi-modal aspects in their UIs. Vibrations as a form of haptics (explained later) can be made part of this user interface by synchronizing vibrations to visual and/or auditory information. Vibrations may be responses to user actions, or just notifications for a passive user. The aim of the vibrations, when used as responses, is not to get attention but to smooth the interaction experience to be more natural. The feedback should be ambient in that it has low cognitive load but it still should make the user experience more pleasant. Gaming is, of course, an exception where sometimes heavy tactile effects are wanted that distract the user.

Utilizing more than two modalities at the same time may not be worthwhile. According to a study (Jacko *et al.* , 2004), trimodal feedback when using a computer may require too much mental resources for the groups of people with no or little computer experience. On the other hand, the study also showed that for experienced computer users, trimodal (visual, auditory, haptic) feedback may yield the best results, because of the amount of information provided. Thus professional equipment might be made better by utilizing all the senses, while equipment directed to mass audience should be more simplified. Natural-like interaction is always welcome to any user, but the problem is what kind of input or output can be produced with a technical device that feels natural to the user. As stated in *Multisensory integration, perception and ecological validity* (Gelder & Bertelson, 2003), experimental results in multi-modality generalize to real life only when the results reflect automatic perceptual processes, in contrast to specific situations like conflicting sensory information.

In a mobile environment, for example when using a mobile device in a city, there are more limitations in perception and action. People pay attention to relevant things only (Milgram, 1970). There may be considerable cognitive load while avoiding bumping into other people and looking out for vehicles. There might be physical stress if one has been walking around the city for hours. Being with a friend or being part of a group while utilizing mobile device might require active social contact with the others while keeping low attention to interacting with the device used. Too complex tactile feedback may thus reduce the effect of tactile feedback in such situation. This further emphasizes how one should not aim directly to use as much multi-modality as possible. Instead, the usage of many modalities should be used to make the usage easier, more accurate with less errors.

1.1.4 Haptics and Vibration

Haptics can be divided into passive and active haptics. Passive haptic properties include the ergonomics of a device in a form of materials, the feel of the keys and other such types of design choices. However, generally the term haptics is used only when the device produces active tactile or kinesthetic feedback to the user. Forms of haptic interaction can be seen in Table 1.1 (Linjama & Kaaresoja, 2003).

Some of the terminology used in the area of haptics is shown in Table 1.2 (Oakley *et al.* , 2000). In particular, it can be seen that in regards to this thesis, the term "tactile" is appropriate when discussing the feedback produced by a vibrating device. The term "tactile" means a subset of the aspects included in the term "cutaneous". Vibrations are specifically causing pressure effects, and they are not, or at least they should not be, producing temperature or pain sensations. Vibrations thus

Table 1.1: Forms of haptic interaction (Linjama & Kaaresoja, 2003).

Interaction	**User**	
Device	Passive (sense of touch, vestibular information)	Active (active motion, manipulation)
Passive - mechanical properties	Machine is in hand	Feel for shape, push keys
Active - programmable properties - generation of force and motion - force feedback of a control device	Vibration alert	Tactile feedback based on application functionality

cause active (from the device point of view) tactile sensations, either for a passive user in the case of vibration alerts or an active user in the case of tactile feedback.

Usage of Tactile Stimulation

Even though the scope of this thesis is limited, usage of tactile stimulation as a form of haptics is studied in a wide range of applications. Tactile feedback can be used as an enhancement in graphical user interfaces for ordinary office applications (Tähkäpää, 2003) (Raisamo, 2002) or games to produce easier or more enjoyable use of various aspects of the UI. The stimulation is done for example with a force feedback mouse. This kind of usage of haptics can bring significant performance increases if properly implemented (Dosher, 2001). One example of a pen giving feedback to the user with vibration is the Nokia Digital Pen (Figure 1.6), which remembers what is written or drawn on digital paper (Nokia Corp., 2004).

Other usage includes various kinds of mobile applications utilizing vibrations to catch attention (mobile phones, pagers etc.), hearing aid via stimulation of the sense of touch in addition to the auditory information, and even pleasure-intended "toys". Tactile feedback is also used directly on displays in the case of touch screens, where the display is an input device as well as an output device. Touch screens allow the user, among else, to touch and drag objects with their fingers (Minsky, 1984). Touch screens with tactile feedback also make a superior temporal discrimination possible, because the sense of touch is about five times faster than vision when rapidly successive data need to be resolved (Geldard, 1960). Recently, there have been attempts to provide realistic feeling of graphical UI elements in also those touch

Table 1.2: Haptics terminology (Oakley *et al.* , 2000).

Term	**Definition**
Haptic	Relating to the sense of touch.
Proprioceptive	Relating to sensory information about the state of the body (including cutaneous, kinesthetic, and vestibular sensations).
Vestibular	Pertaining to the perception of head position, acceleration, and deceleration.
Kinesthetic	Meaning the feeling of motion. Relating to sensations originating in muscles, tendons and joints.
Cutaneous	Pertaining to the skin itself or the skin as a sense organ. Includes sensation of pressure, temperature, and pain.
Tactile	Pertaining to the cutaneous sense but more specifically the sensation of pressure rather than temperature or pain.
Force Feedback	Relating to the mechanical production of information sensed by the human kinesthetic system.

screens that are meant for small devices like mobile phones (Poupyrev & Maruyama, 2003).

Tactile navigation is being studied in the *Active Belt* project (塚田 & 安村, 2001). Active Belt is a wearable belt that gives a user directorial information via tactile stimuli. Since the sense of touch doesn't disturb other senses much, it can be used for daily activities according to the study. The system uses GPS for acquiring location information, with multiple vibration motors and LEDs giving the user navigational and other information.

Perception of Vibration

Vibration is sensed by the mechanoreceptors. The sense of touch is highly sensitive to vibration up to 1000 Hz, with the peak sensitivity around 250 Hz (Bolanowski

Figure 1.6: Nokia Digital Pen (press photo).

et al. , 1988). As mentioned earlier, Pacinian corpuscles are especially associated with perceiving vibration.

The threshold for successiveness (being able to tell that not one but two events occurred) is only about 5 ms for the sense of touch (Heller & Schiff, 1991). This could be interpreted as suggesting that the sense of touch might be a method quick enough for interacting with devices. The perceived overall magnitude of a pair of vibrotactile stimuli is dependent on the relative frequencies of the two stimuli. Summation is greater when one frequency is higher than ca. 40 Hz and one is less than ca. 40 Hz, if compared with a situation where both are higher than or less than 40 Hz (Boff & Lincoln, 1988). The effect could be taken into account when producing vibration that is meant to be clearly felt. The effect is probably caused psychophysically because the frequency range of Meissner's corpuscles, responding to "flutter", ends at about 40 Hz (Bolanowski *et al.* , 1988) or 60 Hz (Wall & Harwin, 2001) depending on the study, while Pacinian corpuscles continue to respond to higher frequencies.

The perceived magnitude of any vibrotactile stimulus is also affected by the placement of the vibration on the body. The sense of touch is most sensitive in places where it's most needed - face, tongue and hands. As an example, a fingertip is ten times as sensitive as one's back (Zimbardo *et al.* , 1995).

Mobile phones, for example, are used near various places of the body, and the characteristics of the tactile contact vary accordingly (Linjama *et al.* , 2003). The phone can be for example in a pocket, on a belt or in hand. Depending on the location, there is either a direct contact to the skin, or there is some material between the phone and skin. Some dampening occurs when a piece of clothing is in

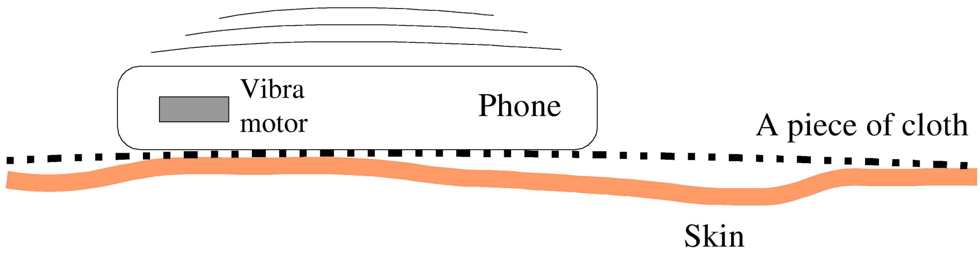

Figure 1.7: Tactile contact characteristics vary according to the usage situation. Here a piece of cloth is between the vibrating device and skin.

the way, which together with an insensitive part of the body (like a leg) may cause the vibration go unnoticed more easily. An example situation is shown in Figure 1.7.

Vibration Motors

Ordinary vibration motors use rotating eccentric shafts that vibrate usually at about 130-190 Hz (Copal, 2004). They are widely used, but have some limitations, the most important being the slow response time. Compared to the threshold of successiveness for the sense of touch, the rising time of intensity for a vibration motor, 100-200 ms, is very high. Raise time means the time it takes for the motor to achieve its full rotational speed, and fall time means the time it takes for the motor to stop from full speed. Raise and fall times may be somewhat reduced by optimizing the voltage inputted to the vibration motor in order to achieve faster start-up and stop (by decelerating).

Loudspeakers can also be used to produce vibration, but only at a relatively low level. There could be, however, a combination of a loudspeaker and a vibrator for small devices. Another form of producing vibrations is to use linear actuator (for example Iwata *et al.* , 2001). In linear actuator there is a moving mass that goes linearly back and forth, thus producing a vibration. The working principle is similar to a loudspeaker. They are quicker to response than eccentric vibration motors, but produce generally weaker vibration.

Piezo actuators are haptic actuators that use piezoelectric material which transduces electrical signals into mechanical motion (Poupyrev *et al.* , 2002). They are used together with tactile displays that convert the mechanical motion into a force communicated to the user. Piezo actuators are very fast, and can have a latency as

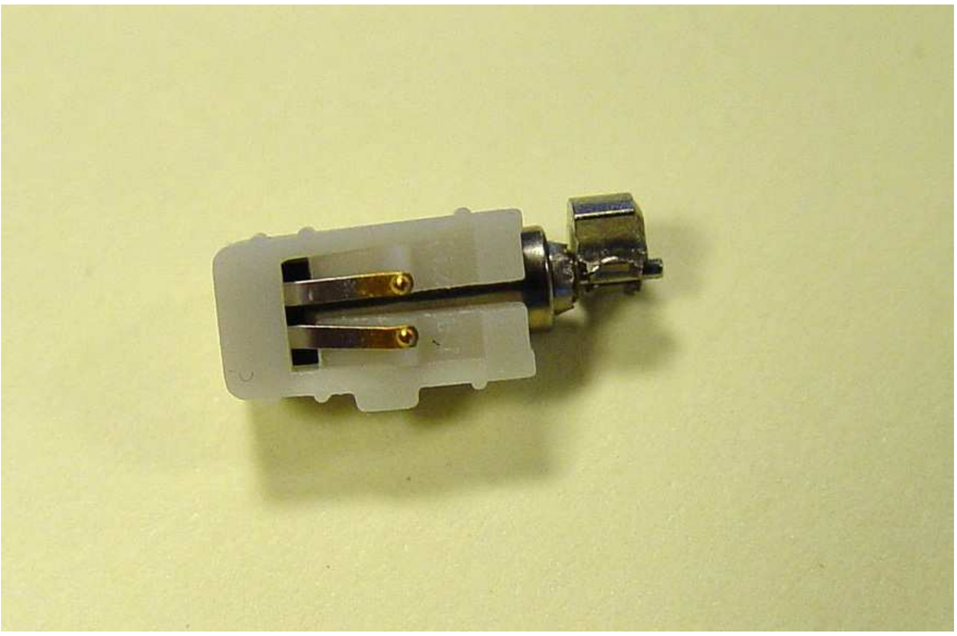

Figure 1.8: A vibration motor with an eccentric shaft. The diameter of the motor is only about 15 mm.

low as 5 ms, which is near the optimal latency for a tactile actuator. Piezo actuators do not produce very strong vibrations, but the quickness allows them to be used for highly interactive tasks like UI feedback.

In this thesis, only devices with eccentric vibration motors are used. An example of such a motor was presented in the beginning of this thesis in Figure 1.8. Vibrations produced by an eccentric vibration motor are one kind of tactile stimuli that can be delivered from a small device. Vibrations are usually used as an alert for calls or text messages, but could also be used, for example, to deliver tactile information at the same time.

This thesis considers human perception and measurement of vibration stimuli, focusing on artificially produced vibrations from a small device. Vibration can be produced, for example, with an eccentric vibration motor that is inserted inside a small device like a mobile phone. Eccentric vibration motors (Figure 1.8) are used in most mobile phones to produce vibration alerts, which is why such a motor is used in the study part of the thesis.

1.2 Objectives and Scope

Existing vibration measurement facilities were set up in a new place and extended to fit the requirements of the measurements that were done later. Some attempts were made to improve the measurement facilities. The main problem with the original measurement facilities is the low frequency vibration that appears in measurement results.

Creation of vibration and auditory stimuli to be used in measurements and user tests with those multi-modal stimuli was studied. A vibration stimulus with the length of circa 100 ms was desired, as it is a typical length for a vibrotactile pulse that is produced by a mobile phone both in the case of a vibration alert and the case of a tactile feedback related to interaction with user interface. It is long enough for the actual vibration to occur, but it can still be classified as a "pulse". Another desired feature was that the vibration stimulus should be symmetric, which means that the raise and fall times of the vibration should be equal. Symmetry was required so that the "shape" of the vibration stimulus would not affect the perception of the stimulus. The auditory stimulus was set to be just a "click", because that is what is usually used in tactile feedback applications like user interfaces.

Measurements and user tests were conducted on the synchronism of auditory and vibration stimuli. Studying perceived synchronism of such stimuli is important in order to understand which kind of timing requirements there would be for vibrations when designing communication devices that utilize feedback via multiple senses. The measurements of the stimuli were done in the vibration measurement facilities. Methods for conducting user tests were constructed so that the user tests could be done with the same stimuli that were already measured. For this thesis, only a brief user study was done on how users perceive the synchronism of the stimuli. The users were asked to answer which they perceived as first, the vibration stimulus or the auditory stimulus.

There are many ways to conduct user tests on the perceived synchronism on multi-modal stimuli. Some studies have been quite close to what this thesis presents, like *The Perception of Cross-Modal Simultaneity* (Levitin *et al.* , 1999) which studies visual-auditory perception. Tactile-auditory (tactile meaning touch) perception has also been studied, though from a different point of view, like for example in *Auditory modulation of tactile taps perception* (Bresciani *et al.* , 2004).

1.3 Hypotheses

1.3.1 1st Hypothesis: Measurement Facilities

An obvious hypothesis is that several of the problems of the original measuring facilities should go away with the modifications done. Low-frequency vibration should be reduced, and environment should be safer from the reliability of the results point of view. Measurements of auditory and tactile stimuli should be possible.

1.3.2 2nd Hypothesis: Symmetric Vibration

The second hypothesis, related to the measurements, is that a sophisticatedly constructed vibration stimulus should look symmetric with properly chosen acceleration and braking periods.

1.3.3 3rd Hypothesis: Effect of Vibration Characteristics on Perceived Synchronism

The third hypothesis, related to the user tests, is that the vibration stimulus is not perceived as happening at the same time with the auditory stimulus if the latter happens at the moment vibration starts. This is because the vibration motor accelerates to its full strength in a certain amount of time.

1.3.4 4th Hypothesis: Temporal Position of Perceived Synchronism

The fourth hypothesis is a more precise version of the third hypothesis. The hypothesis is that the rise and fall times of the vibration motor affect the perception so that the stimuli are perceived as happening at the same time if the auditory click occurs at the peak of the short vibration. Still, another aspect that might affect the results is that it's natural for the sound to occur later (because of the slowness of sound), but not vice versa. A sound stimulus coming a bit late might be interpreted as being synchronous to the vibration stimulus in this case.

1.4 Thesis Structure

This chapter with its many subsections gave the theoretical background for the thesis. In Chapter 2, I represent the measurement facilities and how they were set up. Chapter 3 presents the how the stimuli were created and how the measurements and the user tests were done. Chapter 4 analyzes the solution with regards to the aims of the thesis and considers future prospects, and finally Chapter 5 concludes the thesis with the most important facts learned during the creation of the thesis.

Chapter 2

Measurement Facilities

The measurement facilities are more thoroughly examined in this chapter. The original facilities were moved to a better location and set up there. Once set up, mounting experiments were conducted in order to see if better measurement results could be achieved by mounting the vibrating device differently. The usage of the measurement facilities will continue in Chapter 3.

2.1 Original Facilities

In the beginning of the project the measurement facilities were build on a mechanically non-isolated desk in the middle of a work area. The vibrations from environment caused problems in the measurements of the devices.

The measurement system consisted of a laser that measured the velocity of the vibrations in one axis, and a laptop-connected device that gathered both the information from the laser and from the vibration device. The laser measurement system consisted of a touch-free laser sensor head and a controller. The sensor head was *Polytec OFC 303 Sensor head* (Figure 2.1), and it was connected to a *Polytec OFV 3001S Vibrometer controller* (Figure 2.2).

It was presumed that the velocity information corresponds to the perceived sensation better than displacement or acceleration information. This has been seen for example in *Puhelimen värinähälytyksen mitoituksen optimointi - tutkimushaasteita* (Linjama, 2001), which refers to the ISO standards concerning human response to vibration (ISO, 1995a) (ISO, 1995b). The standards use frequency weighting which according to Linjama actually integrates the acceleration to get velocity, which would indicate that a small device's vibration velocity would correspond to the actual sensation by a human being.

Figure 2.1: Polytec OFC 303 Sensor head.

Figure 2.2: Polytec OFV 3001S Vibrometer controller and Harmonie 01dB measurement device.

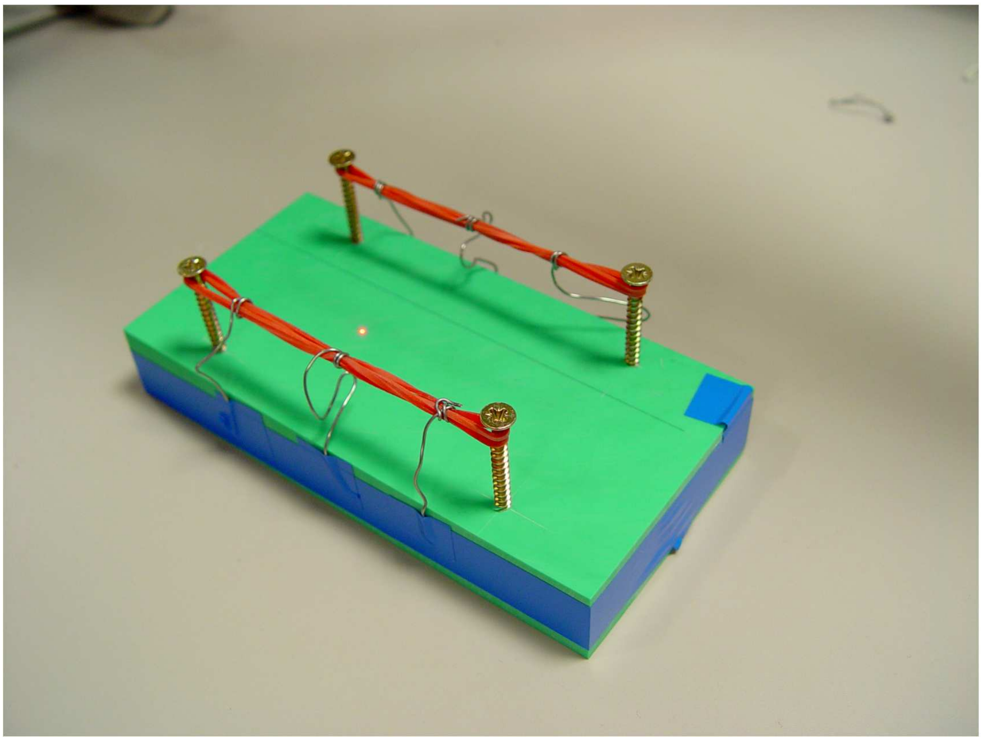

Figure 2.3: A piece of ciba, rubber bands and soldering tin.

From the controller, the velocity information was brought to a four-channel real-time sound and vibration measurement device *Harmonie 01dB* (Figure 2.2, on the top) that had a connector that could be attached to the PCMCIA-slot of the laptop. The velocity information from the laser controller was brought to the device's first channel, and the input voltage from the vibration motor was brought to the second channel. Two channels were left unused.

The device to be measured was placed on rubber bands attached to screws that were driven into the basement made of "ciba", a solid form of polyurethane foam. This is shown in Figure 2.3. The rubber bands were supported by some soldering tin in an attempt to damp the low frequency vibration present.

2.1.1 Problems

There were a number of problems with the original equipment and environment. The equipment was highly influential to especially low frequency vibrations from the environment it resided in, including people walking nearby, closing doors and so on. The rubber bands, while being a relatively good base for the device, had their own low frequency vibration when using a vibrating device.

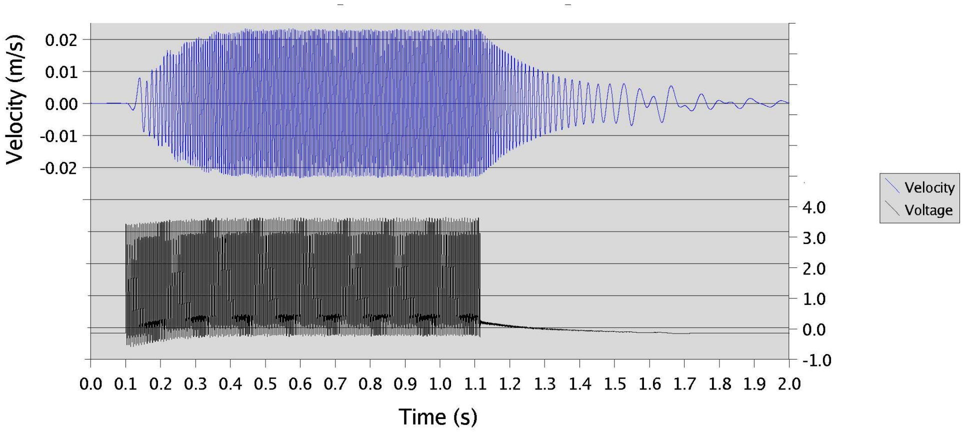

Figure 2.4: Old results.

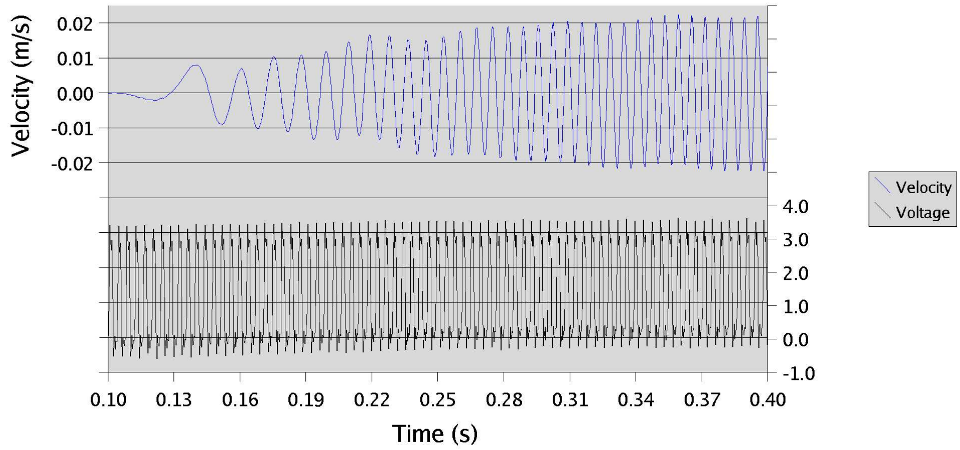

Figure 2.5: Old results, zoom in. Low frequency vibration can be clearly seen.

Some measurements done with the equipment in the old test environment are seen in Figure 2.4. As can be seen from the picture, there is some low frequency vibration present. A zoom-in of the beginning of the vibration is shown in Figure 2.5, which shows the fluctuation of the vibration velocity and the PWM (pulse width modulation) well.

Even though it is out of this thesis's scope in the matter of measurements, it should be taken into account that more thorough haptic and/or multi-modal tests should be possible in the future by expanding the equipment. Thus, there had to be enough expansion capabilities both in terms of room and in terms of equipment features.

2.2 Location and General Setup

The first task was to find a more isolated environment for the measurement facilities. This was found from a basement area, where the equipment could be placed in the same premises as audio testing equipment. This will also allow for easier multi-modal co-operation in the future.

The new area was a low-traffic area with a sturdy concrete floor. The equipment was placed in an open area segment of the room, but the furniture was re-arranged in a way that allowed some isolation from the corridor. Because of the low traffic, there was no environmental disturbance other than what was caused by the testers.

It was found that it was possible to transfer an optical table from other town to our use. The table was very heavy, and seemed like a good candidate for having less environmental influence on the vibration studies, though actual measurements were not done on how much better it really was.

The equipment continued to consist of the devices described earlier. The 4-channel Harmonie system was thought to be future-proof enough (e.g. multi axis velocity input or other additional data). The laptop with which the data was collected was using proprietary software supplied with the Harmonie system. Measurement data was transferred from the test laptop to the workstation laptop with an infrared link. Numerical test data were transformed into a graphical form with a spreadsheet program. Additional image editing and Encapsulated PostScript (EPS) output for LaTeX was done with *The GNU Image Manipulation Program* (The GIMP Team, 2004).

2.3 Mounting Experiments

The low frequency vibrations caused by the rubber bands still existed. Therefore it was decided that some experiments on various mounting methods would be done, to see if there were better alternatives.

Optimally, the results should show a picture like the original results in Figure 2.4, but without the low frequency vibration present and with a somewhat faster decline of the vibrations. In the original results, it seems that the rubber bands stay vibrating for a certain amount of time after the vibration motor has stopped.

2.3.1 Test Setup

The original measurement facilities were described earlier. The connections between the parts of the equipment are shown in Figure 2.6. The settings for the laser sensor

Table 2.1: The laser sensor head settings used during all the experiments and measurements.

Tracking Filter	Slow
Velocity Decoder	DC
Velocity Range	25 mm/s/V
Velocity Filter	16.0 kHz

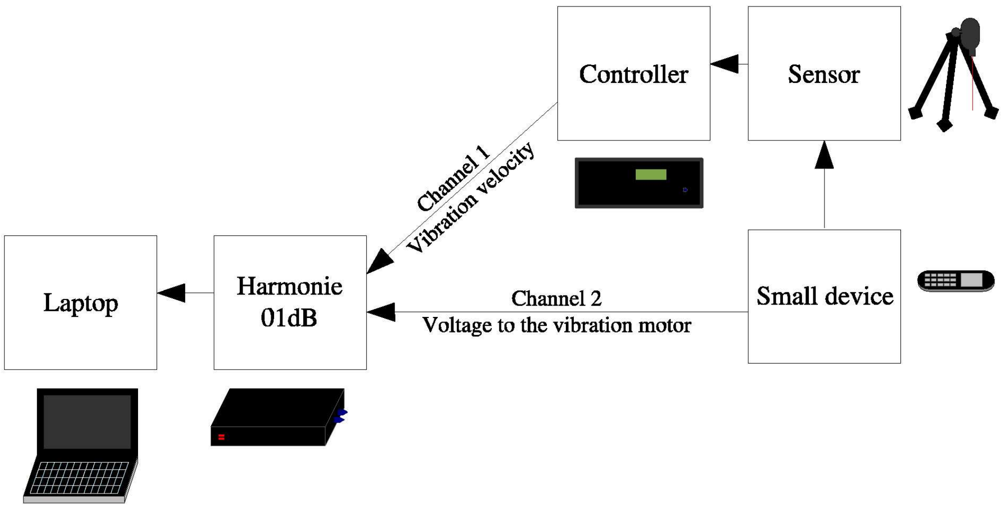

Figure 2.6: A diagram of the equipment used for the old measurements and for the experiments concerning the mounting of the device.

head during all of the thesis are shown in Table 2.1. The vibration motor of one small device (a communication device) was used for 1 second, and the vibration caused by this was recorded. The vibration motor was fed with pulse-width modulated (PWM) voltage.

2.3.2 Results

First, I made an attempt to use fiber glass (Figure 2.7) to damp low-frequency vibrations. The resulting measurement is shown in Figure 2.8. The graph shows a smoother raise and steady on time, but the decreasing of vibrations do not seem very realistic. Fiber glass produced relatively smooth graphs, but the ending seemed abrupt.

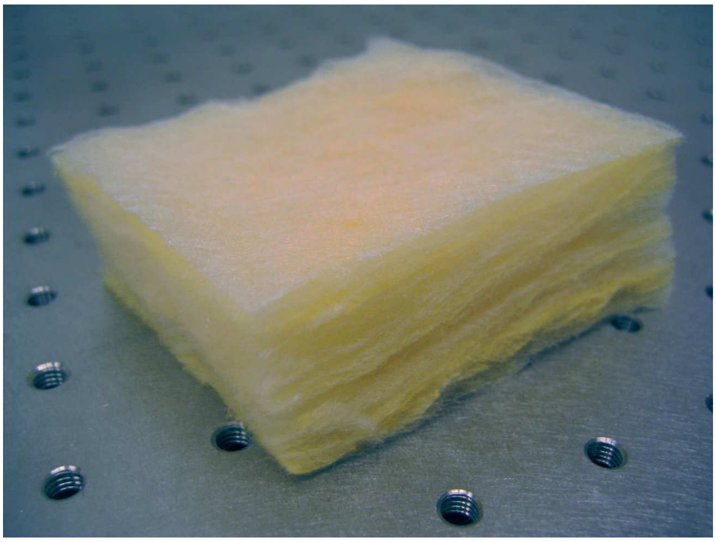

Figure 2.7: Some fiber glass.

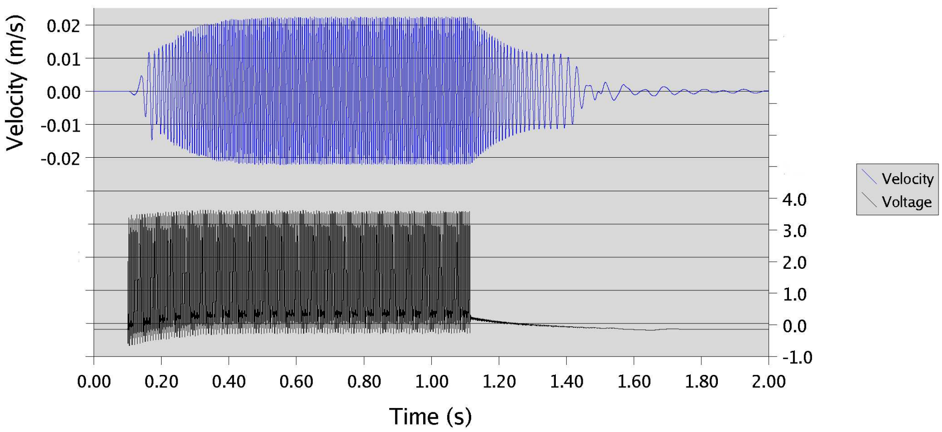

Figure 2.8: Results with fiber glass.

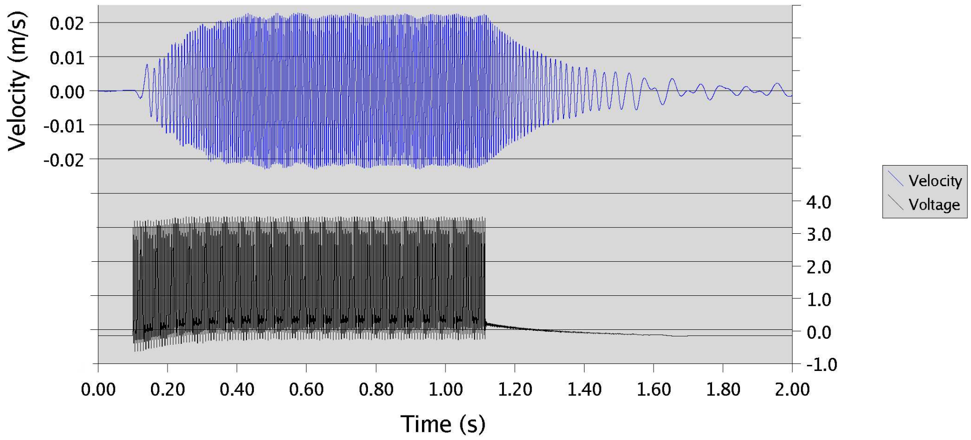

Figure 2.9: Results with rubber bands which were folded two times so that they were fairly tense.

I went back to the rubber bands and tried various possibilities. Depending on the way the rubber bands and the pieces of soldering tin were used, the quality of graphs varied from poor to good. For example, a setup was used where rubber bands were folded two times, and the soldering tin was inserted so that it bent underneath the rubber bands. It was relatively similar setup to the original setup seen in Figure 2.3, but the rubber bands were more tense. The produced measurements (Figure 2.9) were not good because of the low-frequency vibration present. I then used the same rubber bands, but only folded once. I also had the pieces of soldering tin pointed to the center of the rubber bands, where the device to be measured would have its most weight at. However, the results were similarly not very good.

Finally, I found out that the best results are achieved by having the rubber bands folded only once to achieve mediocre tenseness, and by bending the soldering tins beneath the rubber bands in a way that they act as a kind of (low-frequency) vibration absorber for the rubber bands. It seemed like a good idea to keep the pieces of soldering tin pointed toward the centers of the rubber bands. The rubber bands were also twisted around themselves in order to form "holes" through which soldering tin could be injected so that they would not be in direct contact with the vibrating device. The rubber bands and the pieces of soldering tin are shown in Figure 2.10. An example measurement is shown in Figure 2.11. Even though the results aren't perfect, I decided that they are good enough to see how the vibrations actually happen. The rest of the measurements were done with it.

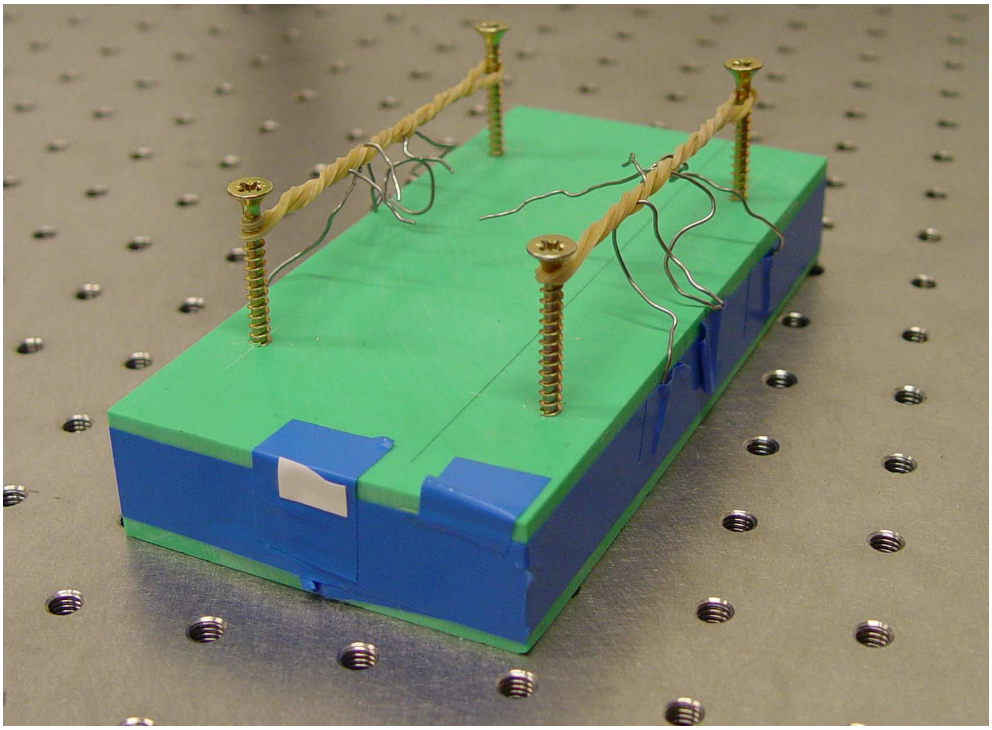

Figure 2.10: The rubber bands and the pieces of soldering tin that are bent under the rubber bands.

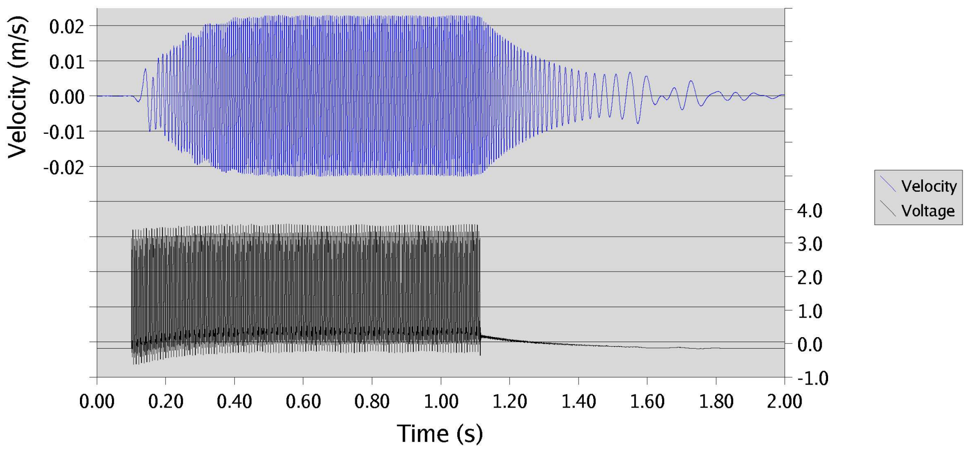

Figure 2.11: Results with rubber bands which were folded once, and with soldering tin bent below the rubber bands. There is less low frequency vibration than in Figure 2.9.

Chapter 3

Study

This chapter presents a method to create multi-modal stimuli, together with information about methods used in and results acquired from the measurements and user tests conducted with the stimuli. We were interested in the measured and perceived synchronism of the stimuli.

3.1 Methods

This section describes the methods used. In the first subsection, *Creating Stimuli*, I will tell how the vibration and auditory stimuli were created. The second subsection, *Measurements*, considers how the measurements were prepared for and how were they conducted. The third and last subsection of the section, *User Tests*, presents how I made the user tests possible.

3.1.1 Creating Stimuli

We wanted to measure and to do user tests of synchronous tactile and auditory stimuli as an example of vibration perception related tests that can be done in the facilities. The synchronization of the two stimuli would be varied, so that the auditory stimulus (a click) would be heard at different phases of the vibration stimulus. The vibration should be a circa 100 ms long and symmetric. Measuring these stimuli should be possible by using the existing measurement facilities.

Device for Producing Stimuli

A box-shaped device built on *BASIC Stamp 2* by Parallax, Inc. was used to output the stimuli. BASIC Stamp 2 itself is a micro-controller device consisting of an

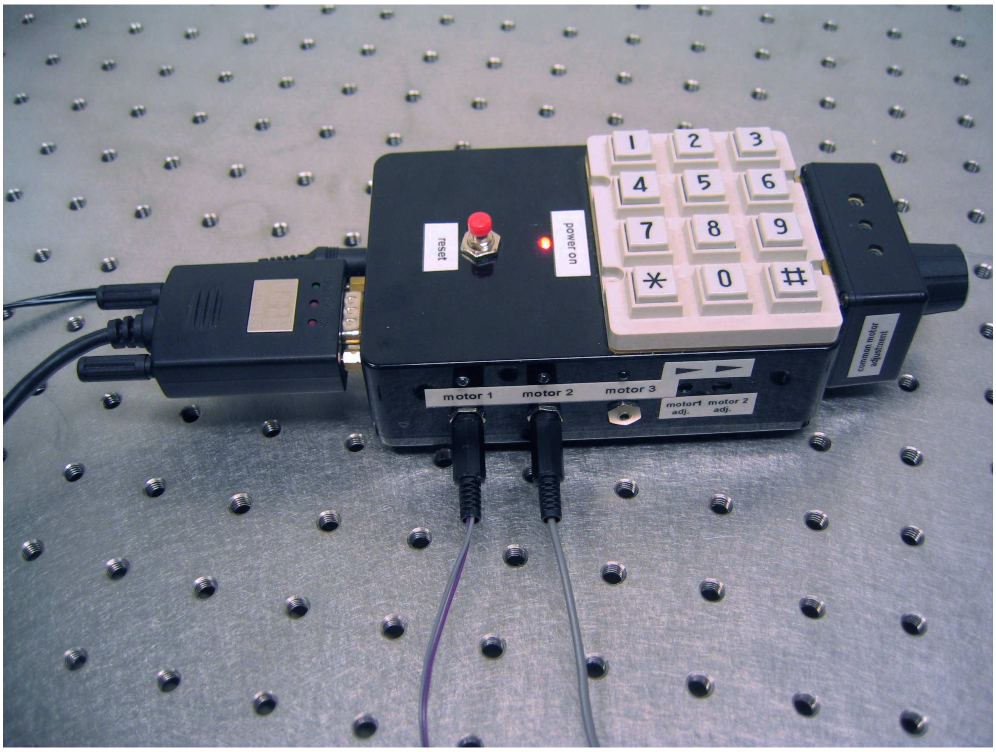

Figure 3.1: The device that was used to feed the vibration motor and the headphones with proper voltages during the measurements and the user tests.

integrated circuit (IC) and the carrier board around it. It can be programmed with a simple programming language, BASIC. The specifications of the device can be seen in Table 3.1 (Parallax, Inc., 2004). As seen there, BS2 has a (RS-232) serial port to which a computer could be connected for transferring data.

The stimulus-producing device was based on BASIC Stamp 2. It was created by others at Nokia Research Center for producing voltages to vibration motors, so it was decided I could utilize it in my study. The device is shown in Figure 3.1. The stimulus-producing device had 3 voltage output channels, each of which could be adjusted with screws. Two of these would be used, one for outputting voltage to the vibration motor and the other for outputting voltage to the headphones. The outputs had 2.5 mm plugs.

Connecting to the Device

An open-source GNU/Linux program, *BASIC Stamp Tools for Linux* (Kendrick *et al.* , 2004), was used for interacting with the stimulus-producing device. The program consists of two parts: bstamp_tokenizer and bstamp_run. The first one

Table 3.1: BASIC Stamp 2 specifications.

Product	BS2-IC
Package	24-pin DIP
Package size	3.05 cm x 1.52 cm x 1.02 cm
Environment	0°C - 70°C
Microcontroller	Microchip PIC16C56c
Processor speed	20 MHz
Program execution speed	~4,000 instructions/sec.
RAM size	32 Bytes (6 I/O, 26 Variable)
Scratch pad RAM	N/A
EEPROM (Program) size	2K Bytes, 500 instructions
Number of I/O pins	16 +2 Dedicated Serial
Voltage requirements	5 - 15 vdc
Current draw @ 5V	8 mA Run / 100 μA Sleep
Source / sink current per i/o	20 mA / 25 mA
Source / sink current per unit	40 mA / 50 mA per 8 I/O pins
PBASIC commands	36
PC programming interface	Serial Port (9600 baud)

takes the source of a computer program programmed with BASIC programming language, and transforms, or tokenizes, it into binary data that can be send to the device. The second one transfers the file to the device via a serial port.

At the time of downloading the current release (dated 15th of May, 2004), the code both in the release and the CVS (Concurrent Versions System) was broken. This was repaired by simply intuition, looking at the program code and the response obtained from the device, and by comparing to an older version of the portion of the program that is responsible for transferring the data to the device. The problem was in the "handshake" portion of the program, responsible for initializing data connection before actual sending of the program data. I reported my findings on the *bstamp-misc* mailing list of the project, so that repairs would be done for the next release.

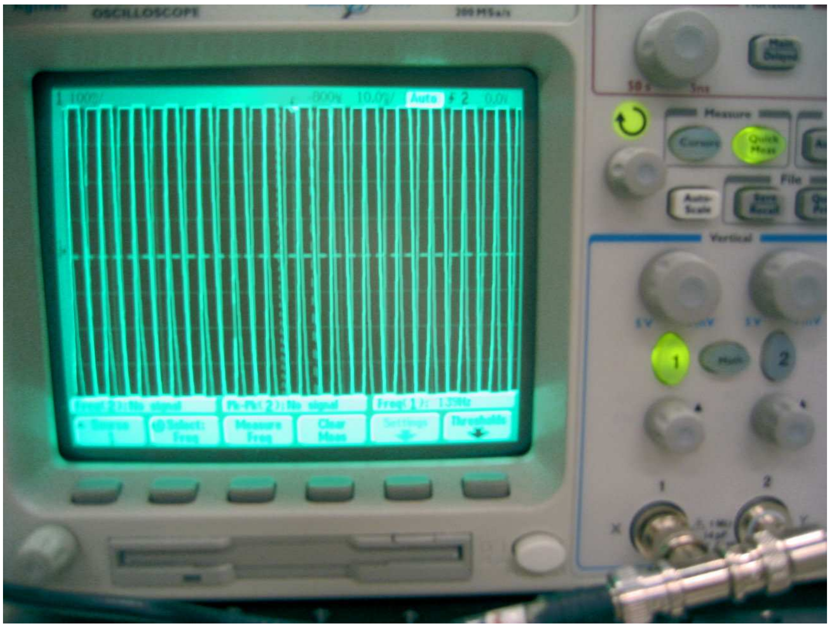

Figure 3.2: The oscilloscope used for the calibration. Calibration was successfully done when the vibration frequency was about 140 Hz.

Calibration

The stimulus-producing device was calibrated so that the voltage fed to the vibration motor of the device being measured would be an amount that is required for achieving the vibration frequency of 140 Hz during steady ca. 40% pulse width modulated voltage. 140 Hz is a typical vibration frequency for an eccentric vibration motor. 40% voltage was used as the calibration signal so that when using full voltage, the same amount of vibration velocity would be achieved in less time. This allows for a quicker vibration stimulus.

The calibration was done by using an oscilloscope (Figure 3.2) and playing a 1 second vibration stimulus.

Tactile and Auditory Stimuli

I started creating my own stimuli, based on the BASIC files I acquired from my instructor. The aim was to produce a “click” signal in audio, and a short vibration as a tactile stimulus. The synchronization of these stimuli would be varied so that the auditory stimulus and the vibration would occur at a different time. The aim was to make a symmetrical vibration stimulus, so that the graph would ideally resemble a isosceles triangle without the bottom part (see Figure 3.3). The symmetry was

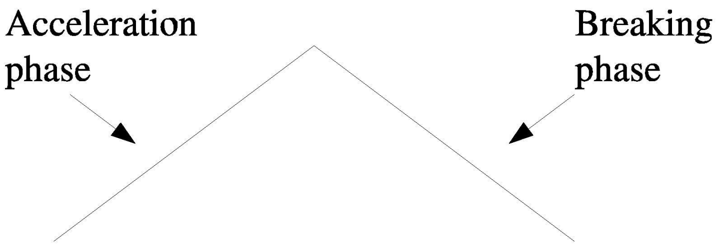

Figure 3.3: Symmetric vibration. An illustration of the vibration envelope I was aiming for.

aimed for mainly because it would prevent changes in perception that might occur because of shorter braking phase. The symmetric shape is also just more beautiful, and it is easily described for reproducing the experiments.

Table 3.2: Some of the BASIC commands used.

Command	**Function**
FREQOUT pin, duration, freq1{,freq2}	Generates one or two sine-wave tones for a specified duration
HIGH pin	Make the specified pin produce full voltage output
PWM pin, duty, cycles	Converts a digital value (duty) to an analog output level
SERIN rpin,baudmode, timeout,tlabel,inputData	Receives asynchronous data and stores it in a variable

Various BASIC commands were used to produce the stimuli, shown in the Table 3.2. The vibration motor needs direct current (DC) which can be accomplished with the BASIC Stamp device, with the *PWM* command (for non-100% voltages) or *HIGH* command (for 100% voltage). A sine wave can also be produced easily with the *FREQOUT* command to create auditory stimuli. With the short stimulus duration used (1 ms), the sine wave produced turned out to be just a “click” coming out from the speaker. The synchronization of these was done by letting the device output DC to the vibration motor as usual, with the possibility of interrupting the

DC output for the 1 millisecond duration of the auditory click used. The interruption occured if the auditory click was either during the acceleration or during the braking of the vibration motor.

A vibration stimulus consisted on two parts, acceleration and braking. In the braking phase, the vibration motor is fed with a negative current so that it would brake. It is important that the braking period's length and the amount of current given during it is just right, because otherwise the vibration motor starts to vibrate again after stopping, but in a different direction.

The time used for acceleration was decided so that the amount of vibration achieved in that time would be approximately the same that is created in the steady state of a vibration pulse when 40% PWM voltage is fed to the vibration motor. A proper time turned out to be 50 milliseconds.

Braking to a full stop usually happens a bit faster than the acceleration, so braking shouldn't be done with full strength, if symmetry is desired. This was achieved by using the *PWM* command for braking so that the braking period's time could be set the same as the acceleration period. The correct strength for the PWM was found by experimenting at the same time when finding out the proper acceleration time. Attempts were made with 50 ms+50 ms (acceleration+braking) and 60 ms+60 ms vibrations, and the former seemed better as the latter produced noticeably heavier vibrations than what was gotten with 40% nominal voltage. In the Figure 3.4, there's an illustration of the 50 ms acceleration and 50 ms braking, with the PWM value of 140(/255) used. It seemed like the best match for a symmetric acceleration and braking (compare to Figure 3.3). In addition to the graphs, the vibration motor was also listened to - if the PWM value was too high, another short sound of vibration was present as the vibration motor started running in the opposite direction.

3.1.2 Measurements

Stimuli

The stimuli used are shown in Table 3.3. The offsets for auditory stimuli were (semi)logarithmically distributed around the middle of the tactile stimulus, where acceleration changes to braking. This was the assumed (in the 4th hypothesis) point where the stimuli would be perceived as being synchronous. A series of these stimulus pairs would be used later in the user tests. In this measurement part, each stimulus pair will be measured.

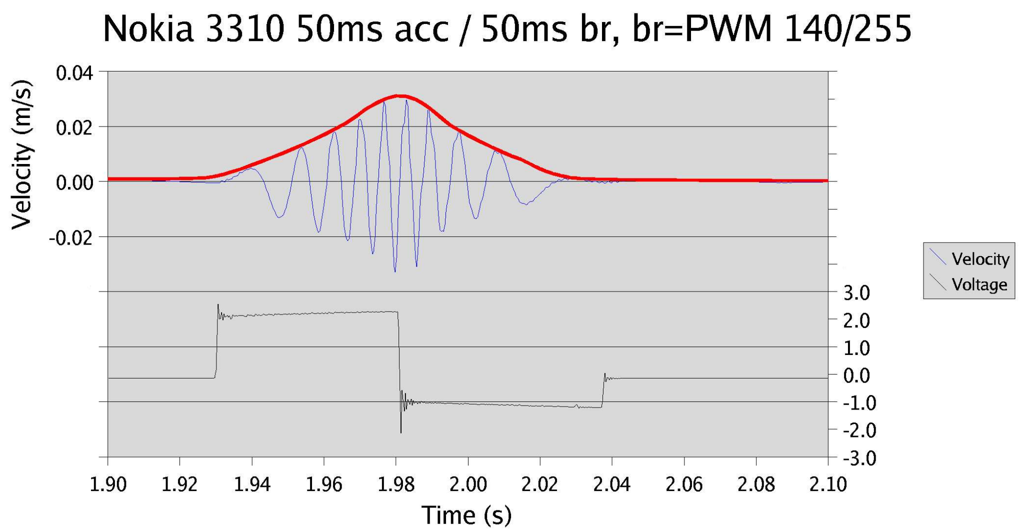

Figure 3.4: The vibration pulse used for measurements and user tests.

Table 3.3: Tactile and auditory stimuli used. The time of the auditory stimulus is related to the middle of the tactile stimulus.

Stimulus number	Tactile stimulus	Auditory stimulus
0	50 ms acceleration at full voltage, 50 ms brake at the strength of 140/255 PWM	-200 ms
1		-100 ms
2		-60 ms
3		-40 ms
4		-20 ms
5		0 ms
6		20 ms
7		40 ms
8		60 ms
9		100 ms
10		200 ms

Test Setup

The test setup was modified so that three inputs were used on the Harmonie 01dB. One input voltage was from the vibrometer, another one from the connector in the stimulus-producing device that outputted voltage to the vibration motor, and the last input voltage was from the connector outputting voltage to the headphones.

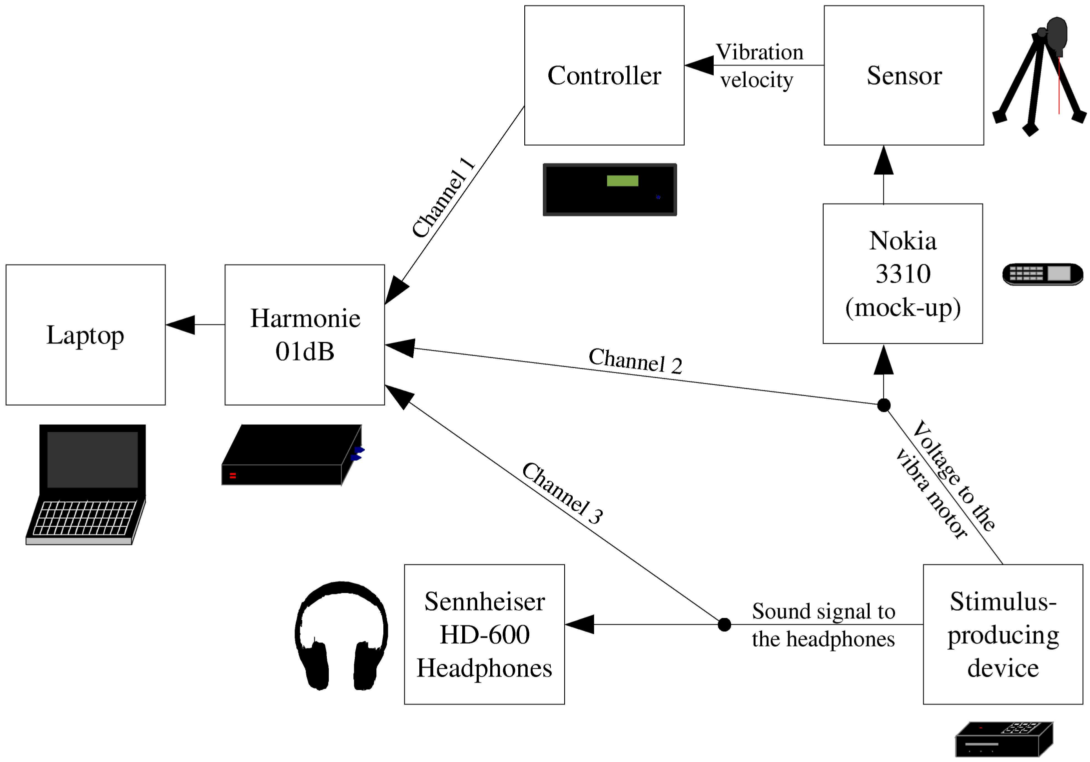

Figure 3.5: A diagram of the test setup for measurements.

This test setup is shown in Figure 3.5.

For the headphones, I needed to solder a 2.5 mm to 3.5 mm connector (the latter which is the standard plug size for headphones). The connector also converted the mono signal to a stereo signal, which was needed for the click to be heard in both ears. The connector is shown in Figure 3.6.

The vibrating device that was measured was an ordinary Nokia 3310 phone (Figure 3.7), to which wires were attached so that the vibration motor could be controlled externally. This was not the same device that was used for the mounting experiments, however. The stimulus-producing device was calibrated as described in an earlier subsection. The headphones used were Sennheiser's model HD-600 headphones.

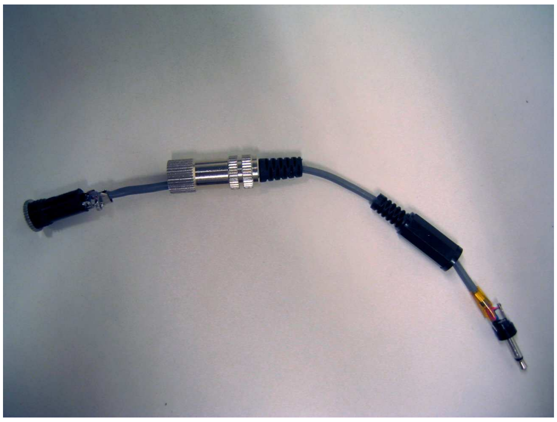

Figure 3.6: The 2.5 mm - 3.5 mm connector that was soldered for the headphones. The 2.5 mm jack was a stereo one, from which both wires were connected to the mono 3.5 mm jack.

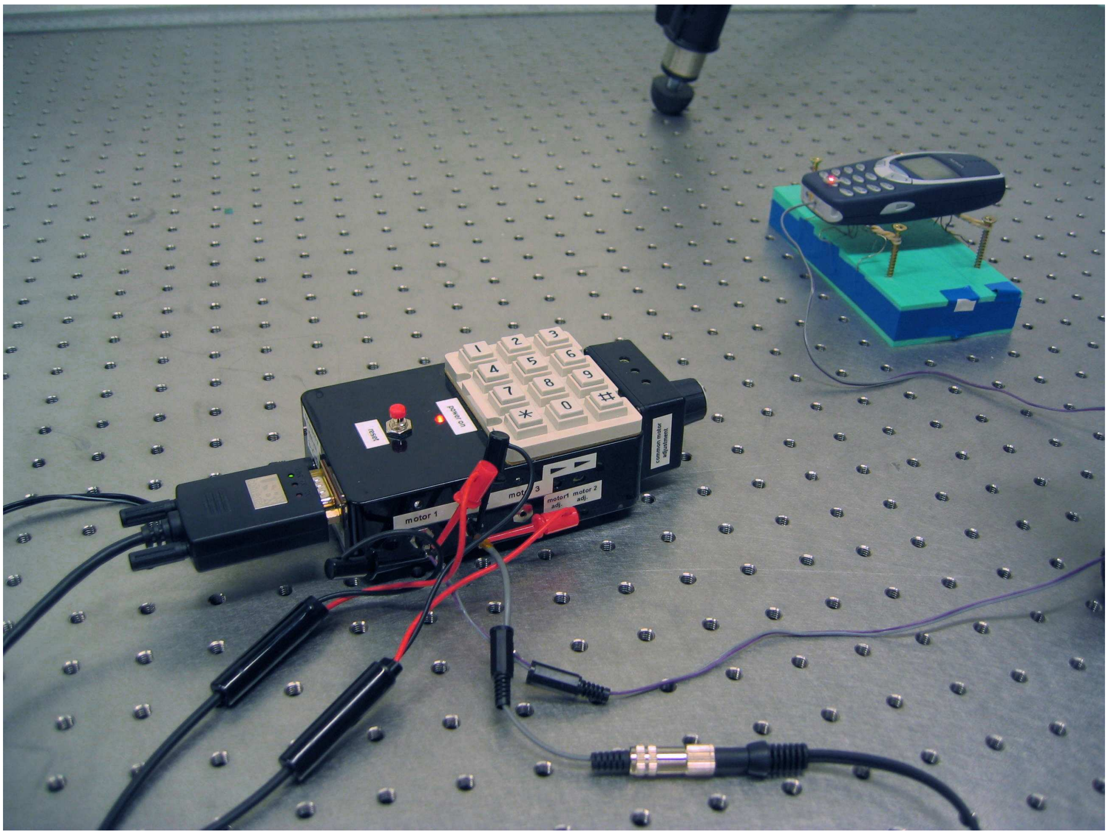

Figure 3.7: Nokia 3310 being measured.

3.1.3 User Tests

Controlling the Stimulus-Producing Device

So far, the device producing the stimuli was used by pressing buttons that were on the device. For remote controlling, the featured serial port was used also for playing the stimuli in addition to loading programs into the device. This was done with the *SERIN*-command, which allowed together with proper parsing to choose stimuli via single characters that are sent. I used the numbers 0-9 and letters * and # for this purpose. * was for the stimulus 10 in the Table 3.3, and # was for a 1 second signal at 40% voltage (PWM) to be used for calibration purposes. Calibration was needed to ensure that a correct voltage was used (i.e. an amount which produced circa 140 Hz frequency with the calibration signal). Without proper calibration the strength of the tactile stimuli could vary as different voltages would be fed to the vibration motor.

Initially, I thought that I would manually use the device to produce the stimuli, and write down the answers from the test person. However, after having gotten the remote control working via the serial port, I figured out that an automatic testing procedure could be made. For that reason, I did the following:

- Replaced the ordinary RS-232 serial cable with an USB-to-serial adapter. This was done because my laptop had a serial port only in its docking station, which is not very mobile. However, the USB (Universal Serial Bus) ports are very commonly integrated in modern computer hardware.
- Wrote a Python UI to control the test procedure, and to collect answers from the user. A picture of the UI is presented in Figure 3.8.

Python (Python Software Foundation, 2004) is a modern programming/script language that is both powerful and relatively easy to use. I used it to create a program (included in Appendix A) that can be used to comprehensively conduct measurements and user tests on various stimuli with the stimulus-producing device. I used Python's access to ncurses-library (The GNU Project, 2004b), which is a library that allows text-mode user interface programming. Text-mode means that there are only characters on the screen, in contrast to graphical mode which is used in graphical desktop environments like KDE (K Desktop Environment), GNOME or the Windows GUI. The Python script itself, called *tactile-audio.py*, was run in a graphical environment (KDE), but inside a terminal window. The terminal window of the Konsole-application was made full-screen, so that there were no background items that could distract the user.

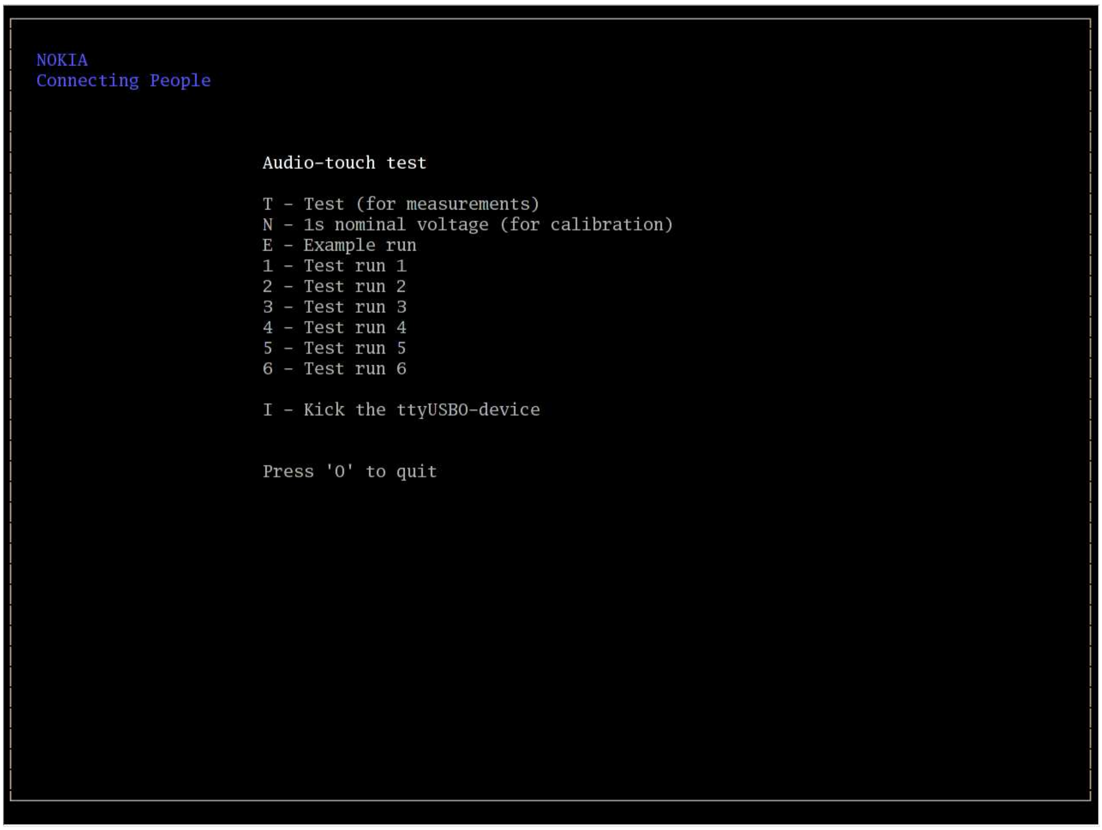

Figure 3.8: The Python user interface programmed for conducting the user tests.

The script allowed the following procedures:

- Test stimuli for measurement - produced all the 11 stimulus pairs in a sequence.
- Nominal - produced a one second 40% vibration signal for calibration (140 Hz) purposes.
- Example run - to be used for introducing a test user to the system.
- Test run N - different test runs for different people.

The example run and test runs also asked the user about how the stimuli were perceived, in addition to playing the stimuli. The user was asked to press *Space* for the next stimulus pair to be played. The program would pause for two seconds, and play the stimuli. Then the program would again halt for two seconds, after which the user was asked which stimulus did he/she perceive as first, the vibration or the auditory stimulus. The answer was written to a CSV (Comma Separated Values) file by the script, and then the user was again asked to press *Space*.

Stimuli Used

The actual test runs were filled with randomized stimuli. The randomization done with the *glibc*'s (GNU C library) *srand48* and *drand48* functions, which produce pseudo-random numbers. The C code for this is included in the Appendix B. There were 6×11 stimulus pairs altogether. Each series of 11 stimuli contained every stimulus pair. Six different test runs were made, which used the same 66 stimulus pairs, but starting at a different point (1, 12, 23, 34, 45, 56) in the series. The randomized order in which the stimuli were played is shown in the Table 3.4. The stimuli themselves ('*' being the stimulus pair 10) were described in the Table 3.3.

Test Setup

The equipment used was mostly the same as earlier, but without the equipment needed for the measurements. This is shown in Figure 3.9. The user tests were conducted in an acoustic listening room, mainly because of the isolation from the environment and the low background noise. The stimulus-producing device was controlled with my own laptop with the Python script described in a previous subsection.

The headphones helped to keep the sound of the vibrating device from being heard, together with the fact that the phone was held in a stretched-out hand. If the user heard the vibration, it could have an effect on when the vibration is perceived

Table 3.4: The order in which the stimuli were played in the user tests. '*' means the 11th stimulus pair. The stimuli were described in Table 3.3.

The beginning of the 1st test run	6	The beginning of the 3rd test run	2	The beginning of the 5th test run	0
	0		4		9
	*		0		8
	3		3		4
	2		*		6
	1		5		2
	5		7		3
	4		1		*
	7		8		5
	9		9		7
	8		6		1
The beginning of the 2nd test run	3	The beginning of the 4th test run	7	The beginning of the 6th test run	*
	4		8		5
	6		1		2
	7		0		8
	2		6		6
	0		3		1
	*		4		4
	9		2		0
	8		5		7
	1		9		3
	5		*		9

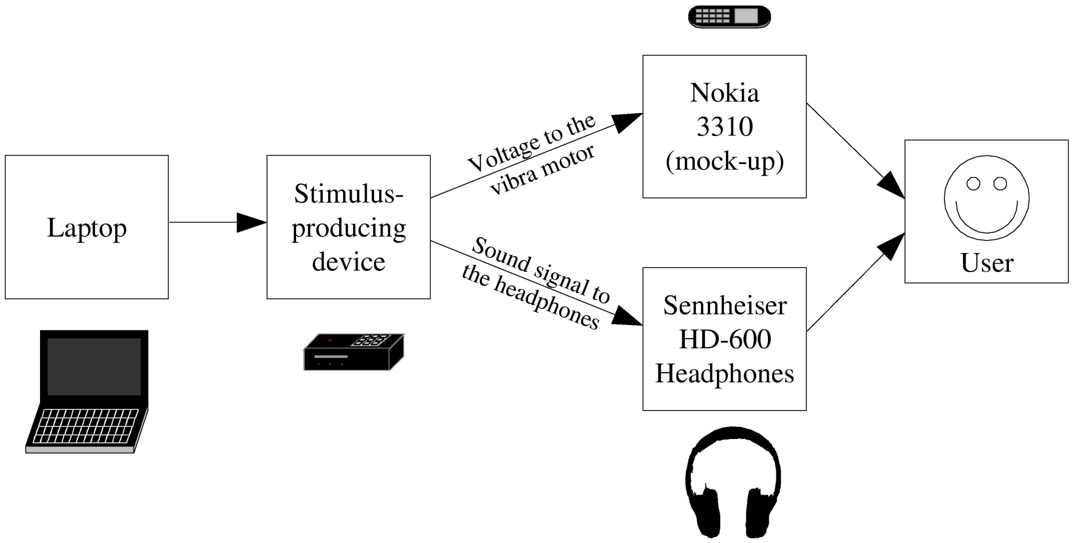

Figure 3.9: A diagram of the test setup for the user tests.

as happening. If the sound of the vibration would have been heard despite these preparations, masking noise could have been played from the headphones.

The equipment was calibrated as before. Users were instructed as follows:

1. Hold the phone in your hand, the hand resting on the leg while sitting.

2. The auditory click may seem a bit loud as it's just a short, sharp click.

3. Tell *which stimulus you perceived as first*, the vibration or audio.

4. It's sometimes difficult to say which one was first.

5. If you don't know what to answer, just try to answer either one anyway.

There were six users in the test. Of these, three were men and the another three were women. Users were 20-35 years old, and they all had a normal hearing. The users were healthy, and none of the users used drugs affecting CNS. I also asked the users about their usage of vibration alert in their mobile phones. The user test was deliberately small because of the scope of this thesis.

A photo of the test situation can be seen in Figure 3.10.

3.2 Results

This section presents the results from the measurements and the user tests. The user tests were done with the same stimuli that were first measured.

Figure 3.10: An user doing the user test.

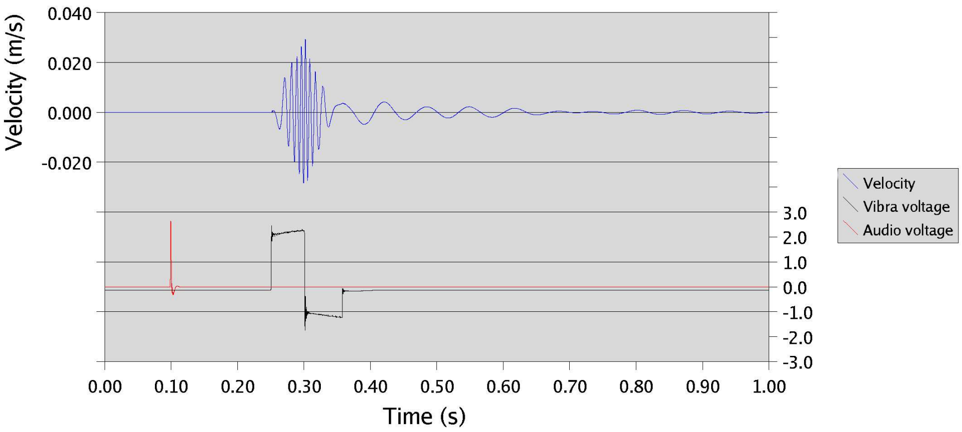

Figure 3.11: Stimulus 0 (offset -200 ms).

3.2.1 Measurements

The measurements were done by playing each of the stimulus pairs in a sequential order. Data collection was triggered by the voltage outputted for the vibration motor, with a delay of -250 ms and a length of 1 second. That means that for each of the stimulus pairs, a 1 second recording starting 250 ms before the start of the vibration stimulus was recorded. The results are presented in Figures 3.11, 3.12, 3.13, 3.14 and 3.15.

The figures shown here are chosen because of the different situations they represent. Figure 3.11 shows a situation where the auditory signal happens before the vibration starts. Figure 3.12 shows a auditory stimulus happening during the acceleration of the vibration motor. Figure 3.13 shows an auditory stimulus at the middle, and Figure 3.14 shows it happening during the braking of the vibration motor. Finally, Figure 3.15 shows an auditory stimulus appearing clearly after the whole vibration stimulus.

There was one interesting aspect in the measurement results that is easily observed. The vibration voltage behaved quite erratically when the auditory beep happened during the vibration motor being active. In Figure 3.14, it behaves like what would be believable - the voltage goes to zero during the small pause it takes to output the auditory stimulus. However, in Figure 3.12 we see something else. The vibration motor voltage seems to actually raise during the auditory stimulus. This is a different situation from the braking phase, because the acceleration is done by the *HIGH* command which activates the stimulus-producing device to continuously transmit the highest voltage possible to the selected pin. This would mean that the

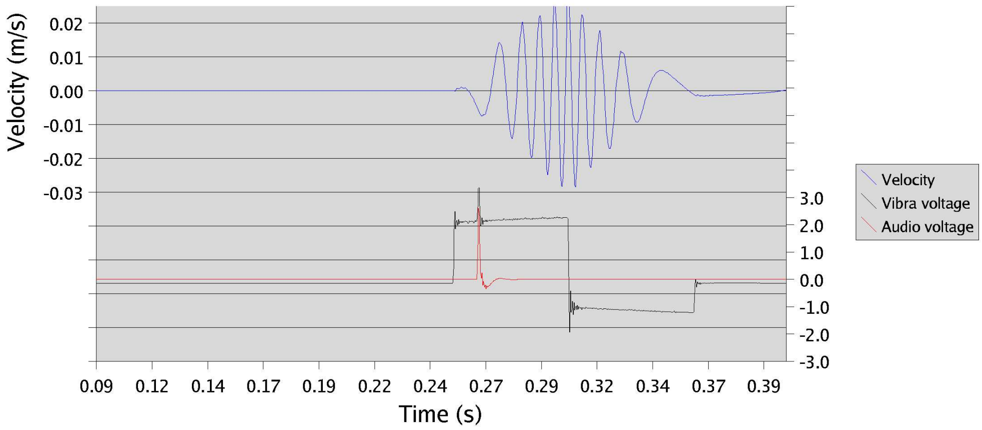

Figure 3.12: Stimulus 3 (offset -40 ms).

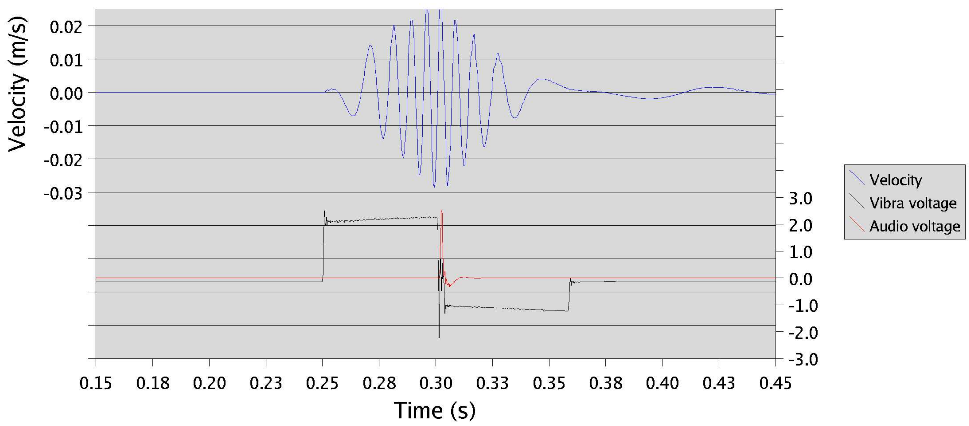

Figure 3.13: Stimulus 5 (offset 0 ms).

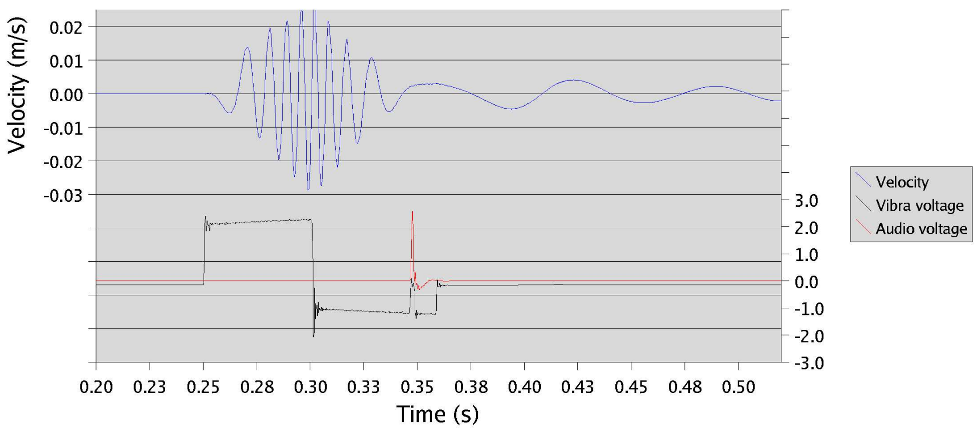

Figure 3.14: Stimulus 7 (offset 40 ms).

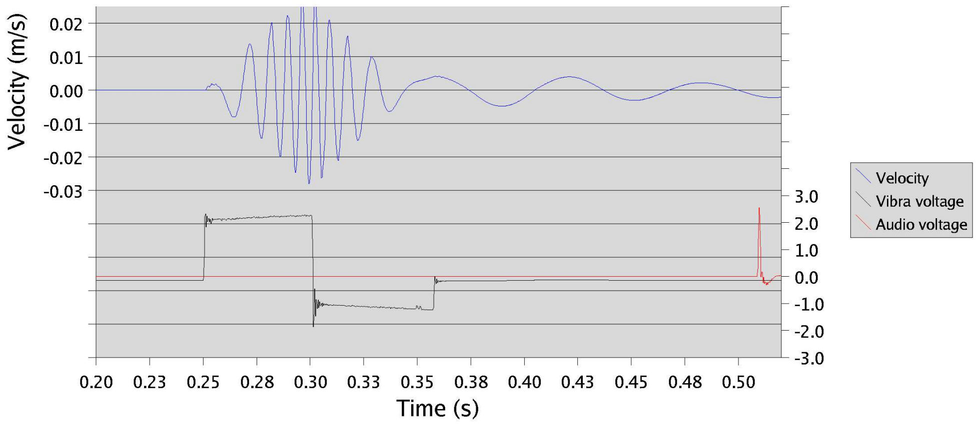

Figure 3.15: Stimulus 10 (offset 200 ms).

expected result in this case is that the voltage stays the same during the auditory stimulus. However, the voltage actually raising from "100%" has to be attributed to some specific feature of the BASIC Stamp device used, when multiple outputs are used at the same time. It also might be a fault in the Harmonie 01dB -device that was used to collect the voltages.

3.2.2 User Tests

The answers were opened in a spreadsheet program and parsed to get statistics. The individual answers are presented in Appendix C. The variation of the results in a form of "auditory first"-answers is presented in Figure 3.16. As can be seen in the picture, there is noticeable variation in how people have perceived the stimuli. On the other hand, the lines are not very linear in many cases, which may mean that the users were not very sure about what to answer, either.

One way to illustrate the significance of the results is to calculate χ^2 (chi square) values to see if specific stimuli were significantly perceived as being not synchronous. The equation for computing chi square values is shown in Equation 3.1. O is the observed value, and E is the expected value. As there were 6 users that were tested, and each stimulus pair was tested 6 times on each person, there were 36 answers to each stimulus pair. The expected value should be the value which reflects a stimulus pair being perceived as synchronous. The χ^2 values were calculated against auditory first answers, so the expected value was set at 18 (auditory first answers). That means that it was expected that there would be a 50% - 50% division between the answers.

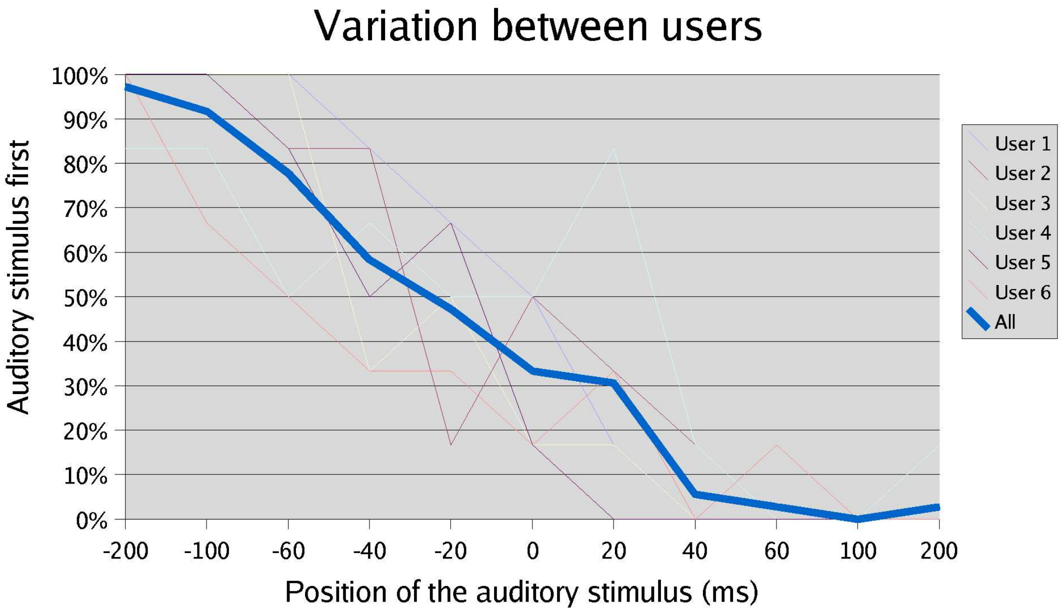

Figure 3.16: The variation of answers among the users.

$$\chi^2 = \frac{\Sigma(O - E)^2}{E} \tag{3.1}$$

The χ^2 values were calculated using the observed values (which were illustrated in Figure 3.16) and the excepted values of 18. A temporal range of one interval (two stimulus pairs) was selected to have χ^2 values with one degree of freedom. The values are shown in Figure 3.17. For example, the χ^2 value for the range 0-20 ms is shown with a mark at the point of 10 ms. The points are connected with lines to approximate the change of confidence in the temporal range. The confidence level means that with higher χ^2 values than 3.84, the expected and observed values do significantly differ. This means that values lower than 3.84 indicate that the values do not significantly differ and the stimuli are perceived as synchronous, which is what we are looking for.

Combining the lines presenting the confidence interval to the Figure 3.16, it is possible to see how the calculated confidence interval looks like when directly linked to the answers. This is presented in Figure 3.18.

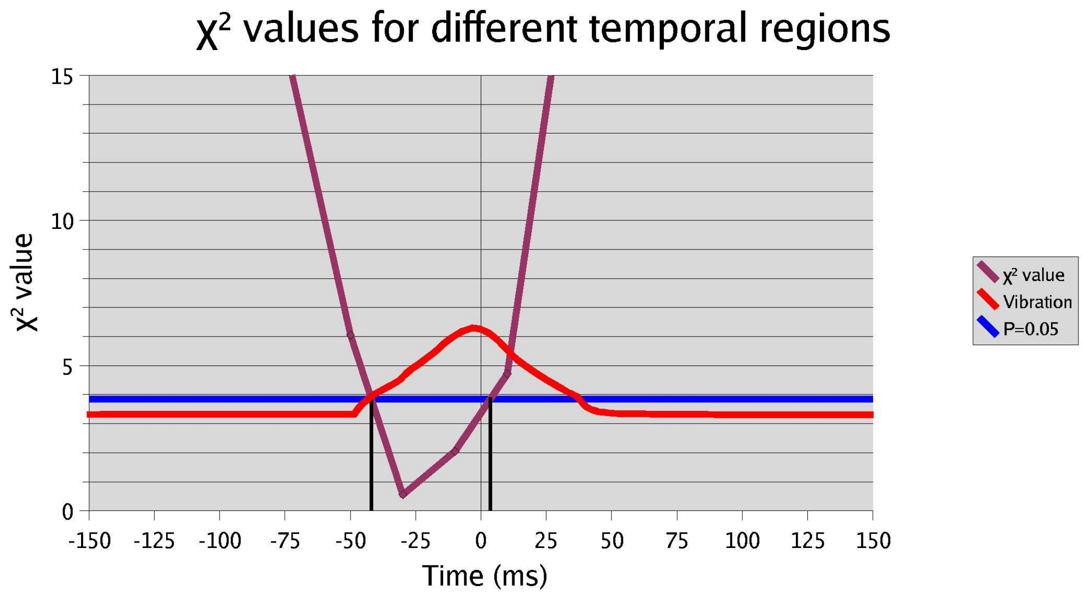

Figure 3.17: The χ^2 values, the level of significance and the vibration envelope. The confidence interval is also shown with black lines. For example, the χ^2 value for the temporal range of 0-20 ms is shown at the point of 10 ms. For df=1 and P=0.05, the χ^2 value for significance is 3.84.

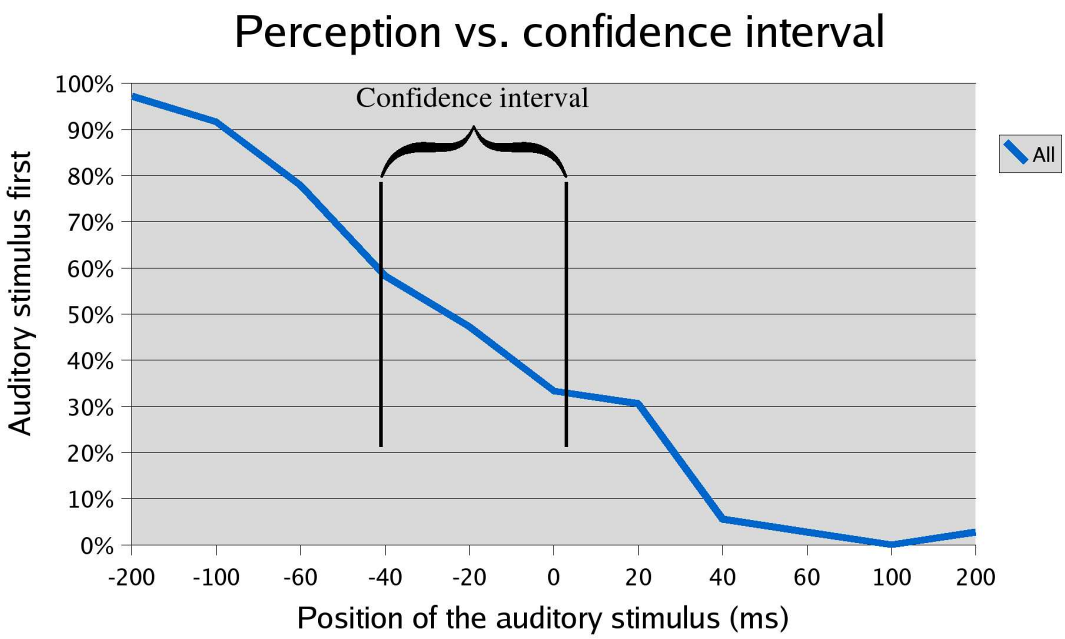

Figure 3.18: The confidence level combined to the answers.

Chapter 4

Analysis

The most important benefits from this thesis include the base work done for creating stimuli, measuring them and conducting user tests on them. Usage of the programmable stimulus-producing device to a greater extent will help future tests using a variety of devices. The Python software will help to control measurements more easily, and especially it will help to conduct user tests. The software can also be easily extended to fit new kinds of user tests.

4.1 Hypotheses

4.1.1 1st Hypothesis: Measurement Facilities

The new environment is adequate for conducting vibration measurements where the environment should not be disturbing the results. The changes done to the facilities were useful, but not remarkable from the pure measurements point of view. It seemed to be hard to find ways to mount a vibrating device so that it both allows free vibration and dampens the low-frequency vibrations. It would be possible to post-process the data by using a high-pass filter to filter out frequencies under 10Hz, but it would have been problematic because it would also affect the beginning and the end of a vibration stimulus. One way, out of the scope of this thesis, would be to use a pneumatic device that would keep the device in the air by means of pressure air. However, implementing such a device for small devices that have quite asymmetric shapes could be a little too difficult considering the benefits.

It is now possible to measure auditory, tactile and also other stimuli within the facilities. The measurements of the auditory-tactile stimuli showed results that were what was expected. The main area of study is the field of haptics, but it is also possible to combine multiple modalities.

4.1.2 2nd Hypothesis: Symmetric Vibration

A symmetric vibration stimulus was successfully achieved, as can be seen from the shape of the measured vibration. Proper braking voltage depends on the vibration motor used, and can be found by experimenting. The easiest way to find the correct braking voltage is to listen to the vibration motor using full acceleration and different voltages driven to the motor during the braking phase. This can be accompanied with measurements to see if true symmetry was achieved.

4.1.3 3rd Hypothesis: Effect of Vibration Characteristics on Perceived Synchronism

The hypothesis proved to be correct. According to the test results, it seems that the tactile and auditory stimuli are not perceived as happening at the same time when the auditory stimulus happens at the time when the vibration starts. This is natural because the vibration motor takes time to reach full vibration strength, and also because the tactile stimulus lasts for 100 ms while the length of the auditory stimulus is only 1 ms.

On the other hand, some people perceived vibration stimulus as being first even if the auditory stimulus happened even before the vibration stimulus started. This, in addition to the variation in the user test results, indicates that the area of perceived synchronism is relatively wide (so that people have to guess) or that people perceive the synchronism differently at least in a test situation like this.

The system producing the stimuli was calibrated according to the stimuli. In many perception tests, stimuli are calibrated so that the perceived sensation intensity is the same for each test person. However, in these tests the stimuli were the subject of the study, not the test persons themselves.

4.1.4 4th Hypothesis: Temporal Position of Perceived Synchronism

The hypothesis stated that the stimuli are perceived as happening at the same time if the auditory click occurs at the peak of the short vibration, where acceleration turns into braking. From the Figure 3.16 it can be seen that the temporal position of 50% - 50% answers is at about -30 ms (or 20 ms after the start of the vibration), and that the derivative of auditory first -answers around that temporal area is quite constant. Looking at the χ^2 values in Figure 3.17, the region of perceived synchronism is about -41 ms to +4 ms from the middle. The hypothesis is true according to this analysis in that the middle of the vibration falls inside the confidence interval at the confidence level of $P = 0.05$, though barely. The vibration is starting to dominate by the time the vibration has been accelerating for 50 ms.

Some of the users mentioned using vibration alert regularly, which may mean that they direct their attention mainly to the vibration. The law of prior entry, described in for example *Visual Prior Entry* (Shore *et al.* , 2001), states that attended stimuli are perceived prior to unattended stimuli.

The results vary a lot between the users, as seen in the Figure 3.16, so the summed-up results should be taken with a grain of salt. A more thorough user study or a different kind of question to the users might be beneficial in order to more accurately determine the perceived synchronism. A better question might have been, for example, "Were the stimuli synchronous?", optionally with some kind of confidence rating.

4.2 Future Work

Other methods of mounting the device to be measured could be introduced. If the whole device does not vibrate (like for examples in the case of button presses), it's better to truly fix the position of the device instead of letting it freely vibrate. This can be accomplished by for example a screw vice to which the device is fixed.

As a continuum to the study presented in this thesis, it would be possible to use a longer tactile pulse, for example 1 second. In that case there would be a long steady phase between acceleration and braking. The user could be asked if the sound stimulus was perceived before or after the start of the vibration. There would also be the possibility to observe if the perceived synchronism of tactile-audio stimuli changes with the variation of the length of the tactile stimulus.

Because of the flexibility of the facilities, other modalities could be introduced. For example, tactile stimuli could be studied together with flashing lights or other kinds of visual stimuli. Tactile+visual+auditory-combinations would also be possible.

The study conducted in this thesis is related more to the actual stimuli than the person receiving them. It would also be possible to conduct tests that focus more on the test person itself. These tests could include for example tests related to how irritating it is to receive non-synchronous stimuli, when expecting synchronous stimuli, with various stimuli and modality combinations.

There are also other, more broad concepts that could be studied in the mobile context. For example, the effects that vibration has on the hand movement, device usability or display readability have already been studied (Boff & Lincoln, 1988), but mainly with for example whole-body vibration instead of small device vibration.

Chapter 5

Conclusions

This thesis was started in order to more properly study vibrations, by making the existing equipment better. Multi-modality and haptics were matters that were supposed to be kept in mind while exploring possibilities. The result is that there are now proper facilities for doing both measurements and user tests on small vibrating devices. In addition to the building of the facilities, a complete test was done involving measurements and user tests on multi-modal stimuli.

The results from the tests were analyzed, showing that the creation of the specified tactile-auditory stimuli was successful. Results from the user tests indicate that the auditory stimulus and the vibration were perceived as synchronous (50% - 50% division between the answers) when the sound occurred 20 ms from the beginning, or 30 ms before the middle of the vibration stimulus which was thought to be the temporal position of synchronism. However, the middle of the vibration stimulus also fell inside the confidence intervals of synchronism. The results from the user test conducted should be interpretted as being only trendsetting, because with the amount of users used in the test the variation between the users turned out to be noticeable.

Synchronism of multi-modal stimuli is interesting from two points of view. First, information about the perception of multi-modal stimuli helps us understand how the human senses work. Secondly, information about synchronism is needed in technical applications like mobile phones in situations where for example something happening on the display needs to feel like happening at the same time as the tactile feedback involved. Because the current vibration motors need some time to accelerate, it is important to know how much before the vibration motor needs to be started so that the feedback does not seem out of place. According to this study, the tactile stimulus is noticed quite quickly after the beginning with a short tactile stimulus, even if the vibration has not reached its maximum.

The system built can be used in future multi-modal and haptic perception experiments. Creation of multi-modal stimuli is already covered by this thesis, and the facilities can be extended to produce different kind of stimuli or stimuli in other modalities. Perceived synchronism of different stimuli in various modalities could be studied almost instantly after creating the stimuli. Haptics, which means the whole field of tactile and kinesthetic feel, is an area which should be explored more thoroughly in the future. The current measurements facilities are suitable to mostly static (non-moving) vibrating devices, and possibilities to extend it to other fields of haptics could be studied.

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Appendix A

Program for the User Tests

This is the Python script programmed for the user tests and also for the measurements. It should be usable on UNIX-like platforms unmodified, and only slight changes are necessary to make it platform-independent.

```
#!/usr/bin/env python

# Testing perception of tactile and auditory stimuli with a BS2-box.
# The main program is after the functions.
#
# Written by Timo Jyrinki
#
# Started August 2nd, 2004
# Last continued on August 16th, 2004
#
# (c) Nokia Research Center 2004

import string,sys,os,time,curses,curses.wrapper,curses.textpad

# Draws the window
def draw_window(stdscr, run_type):
    stdscr.bkgd(' ',curses.color_pair(1))
    stdscr.erase()
    stdscr.border()
    stdscr.addstr(2,3,'NOKIA',curses.color_pair(2)|curses.A_BOLD)
    stdscr.addstr(3,3,'Connecting People',curses.color_pair(2)|
    curses.A_BOLD)
    stdscr.addstr(7,25,'Audio-touch test',curses.A_BOLD)
    stdscr.addstr(22,25,'Press \'0\' to quit')
    if run_type == 'measurements':
        stdscr.addstr(9,25,'Measurement stimulus nr. '+str(f)+'/'+
```

```
        str(len(stimuli)-1)+'   ')
    if run_type == 'nominal':
        stdscr.addstr(9,25,'Playing nominal vibration '+str(f+1)+'/'+
        str(len(stimuli))+'   ')
    if run_type == 'example':
        stdscr.addstr(9,25,'Example stimulus nr. '+str(f+1)+'/'+
        str(len(stimuli))+'   ')
    if (run_type >= 1) & (run_type <= 6):
        stdscr.addstr(9,25,'Test '+str(run_type)+', stimulus nr. '+
        str(f+1)+'/'+str(len(stimuli))+'   ')
    stdscr.refresh()

# Asks the user to select the test to be used
def select_test(stdscr):
    global c
    draw_window(stdscr, '')
    stdscr.addstr(9,25,'T - Test (for measurements)')
    stdscr.addstr(10,25,'N - 1s nominal voltage (for calibration)')
    stdscr.addstr(11,25,'E - Example run')
    stdscr.addstr(12,25,'1 - Test run 1')
    stdscr.addstr(13,25,'2 - Test run 2')
    stdscr.addstr(14,25,'3 - Test run 3')
    stdscr.addstr(15,25,'4 - Test run 4')
    stdscr.addstr(16,25,'5 - Test run 5')
    stdscr.addstr(17,25,'6 - Test run 6')
    stdscr.addstr(19,25,'I - Kick the ttyUSB0-device')
    stdscr.refresh()
    curses.flushinp()
    c = stdscr.getch()
    while (c != ord('t')) & (c != ord('n')) & (c != ord('e')) &
    (c != ord('1')) & (c != ord('2')) & (c != ord('3')) &
    (c != ord('4')) & (c != ord('5')) & (c != ord('6')) &
    (c != ord('i')) & (c != ord('0')):
        c = stdscr.getch()

# Rotates the stimuli order for different test runs
def rotate_stimuli(test_run, howmuch):
    for i in range (howmuch):
        tmp=test_run[len(test_run)-1]
        for j in range(len(test_run)):
            if j == 0: test_run[len(test_run)-1]=test_run[j]
            if (j > 0) & (j < len(test_run)-1): test_run[j-1]=test_run[j]
            if j == len(test_run)-1: test_run[j-1]=tmp
    return test_run
```

```
# Waits for Space button to be pressed
def wait_for_user(stdscr, run_type):
    global c
    draw_window(stdscr, run_type)
    stdscr.addstr(14,25,'Press Space for the stimulus')
    stdscr.refresh()
    curses.flushinp()
    c = stdscr.getch()
    while (c != ord(' ')) & (c != ord('0')):
        c = stdscr.getch()
    draw_window(stdscr, run_type)

# Plays the actual stimulus
def play_stimulus(stdscr, tty):
    stdscr.addstr(14,25,'Playing the stimulus...')
    #DEBUG
    #stdscr.addstr(16,25,stimuli[f])
    stdscr.refresh()
    time.sleep(2)
    tty.write(stimuli[f])
    tty.flush()
    time.sleep(2)

# Asks the user for feedback and writes the answer to a CSV file
def get_feedback(stdscr, run_type, name):
    global c
    draw_window(stdscr, run_type)
    if (run_type == 'measurements') | (run_type == 'nominal'): return
    stdscr.addstr(14,25,'Which did you perceive first, vibration (V) or')
    stdscr.addstr(15,25,'auditory click (A)?')
    stdscr.refresh()
    curses.flushinp()
    c = stdscr.getch()
    while (c != ord('v')) & (c != ord('a')) & (c != ord('0')):
        c = stdscr.getch()
    if (run_type == 'example'): return
    # Write answer to a file
    log=open('tr'+str(run_type)+'_'+name+'.csv','a')
    log.write(stimuli[f]+','+chr(c)+'\n')
    log.flush()
    log.close()

# THE MAIN PROGRAM
```

```
#

def program(stdscr):
    global c,f,stimuli

    curses.curs_set(0)
    curses.init_pair(1, curses.COLOR_WHITE, curses.COLOR_BLACK)
    curses.init_pair(2, curses.COLOR_BLUE, curses.COLOR_BLACK)

    # Set serial port to speed 19200bps, 8N1
    sttycall=os.popen('stty -F '+device+' speed 19200 time 5 ignbrk
    -crtscts -icrnl -opost -onlcr -isig -icanon -iexten -echo -echoe
    -echok -echoctl -echoke','r')
    sttycall.read()
    sttycall.close()

    # Selecting the test
    select_test(stdscr)
    if c == ord('0'): return

    measurements=['0','1','2','3','4','5','6','7','8','9','*']
    nominal=['#']
    example_run=['5','9','2','3','*','0','1','7','8','4','6']
    test_run=['6','0','*','3','2','1','5','4','7','9','8','3','4','6',
      '7','2','0','*','9','8','1','5','2','4','0','3','*','5','7','1',
      '8','9','6','7','8','1','0','6','3','4','2','5','9','*','0','9',
      '8','4','6','2','3','*','5','7','1','*','5','2','8','6','1','4',
      '0','7','3','9']
    if c == ord('t'):
        run_type='measurements'
        stimuli=measurements
    if c == ord('n'):
        run_type='nominal'
        stimuli=nominal
    if c == ord('e'):
        run_type='example'
        stimuli=example_run
    if c == ord('1'):
        run_type=1
        stimuli=test_run
    if c == ord('2'):
        run_type=2
        stimuli=rotate_stimuli(test_run, 11)
    if c == ord('3'):
```

```
        run_type=3
        stimuli=rotate_stimuli(test_run, 22)
    if c == ord('4'):
        run_type=4
        stimuli=rotate_stimuli(test_run, 33)
    if c == ord('5'):
        run_type=5
        stimuli=rotate_stimuli(test_run, 44)
    if c == ord('6'):
        run_type=6
        stimuli=rotate_stimuli(test_run, 55)
    if c == ord('i'):
        # This is just a hack/try, the AT-command has nothing to do with
        # anything but that something needs to be done to wake the buggy
        # USB-to-serial adapter (and minicom seems to kick the device
        # in the right way)
        draw_window(stdscr, '')
        tty=open(device,'w+')
        time.sleep(1)
        tty.write('\r')
        tty.flush()
        time.sleep(1)
        tty.write('AT S7=45 S0=0 L1 V1 X4 &c1 E1 Q0\r')
        tty.flush()
        time.sleep(3)
        tty.close()
        return

    # Asking the user name
    name=''
    if (run_type >= 1) & (run_type <=6):
        draw_window(stdscr, '')
        stdscr.addstr(9,25,'Please enter your name: ')
        stdscr.move(9,49)
        stdscr.refresh()
        namescr=curses.newwin(1,25,9,49)
        namebox=curses.textpad.Textbox(namescr)
        name=namebox.edit()
        stdscr.addstr(11,25,'Name: '+name)
        stdscr.getch()

    draw_window(stdscr, '')
    stdscr.addstr(9,25,'Press Space to start test '+chr(c))
    curses.flushinp()
```

```
    c = stdscr.getch()

    while (c != ord(' ')) & (c != ord('0')):
        c = stdscr.getch()
    if c == ord('0'): return

    # Running the test
    tty=open(device,'w')

    for f in range(len(stimuli)):
        wait_for_user(stdscr, run_type)
        if c == ord('0'): return
        play_stimulus(stdscr, tty)
        get_feedback(stdscr, run_type, name)
        if c == ord('0'): return

    tty.close()

    # End of test
    draw_window(stdscr, '')
    stdscr.addstr(9,25,'Thank you!')
    stdscr.addstr(14,25,'Press Space to go back to the menu.')
    curses.flushinp()
    c = stdscr.getch()

# Main program
global c,device
c=0
device='/dev/ttyUSB0'
while c != ord('0'):
    curses.wrapper(program)
print('Exitted the program.\n')
sys.exit(0)
```

Appendix B

Randomization of the Stimuli

This is the C-code which was done in order to produce the stimuli series in a random order. It can be compiled using GCC (The GNU Project, 2004a) with the following command: *gcc generate_tests.c -o generate_tests*.

```
/* generate_tests.c
 *
 * Outputs 66 random numbers between 0 and 10, 6 series of 11 numbers.
 * Each series will contain only one instance of each number.
 * (10 will be output as '*')
 */

#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <string.h>

int main(void)
{
  int i, j, current_nr, proper_nr;
  char used_numbers[20]="";
  char temp[8]="";
  char current_nr_as_char;

  /* Initialize the random generator */
  srand48(time(NULL));

  for (i=0; i<6; i++) {
    for (j=0; j<11; j++) { used_numbers[j]=' '; }

    /* Output only "proper numbers" which haven't been used yet in
```

```
       this series of 11 numbers */
    for (j=0; j<11; j++) {
      proper_nr=0;

      while (!proper_nr) {
        /* New random number */
        current_nr=(int)(drand48()*11.0);
        /* Convert the random number to a character */
        if (current_nr == 10) {
          current_nr_as_char='*';
        }
        else {
          sprintf(temp,"%d",current_nr);
          current_nr_as_char=temp[0];
        }
        /* If the current number wasn't used, quit the while-loop */
        if (strchr(used_numbers, (int)current_nr_as_char) == NULL) {
          proper_nr=1;
          used_numbers[current_nr]=current_nr_as_char;
        }
      }

      /* Output the random number to screen */
      printf("'%c',", current_nr_as_char);
    }
  }
  printf("\n");
  return 0;
}
```

Appendix C

User Test Answers

These are the original answers from the user tests. The answers are sorted according to the stimulus pair, but are otherwise untouched. Each user had a different test run (*tr*) that was run for him/her. The stimuli were presented in Table 3.3, and the test runs in Table 3.4.

User 1	**tr2**	**User 2**	**tr3**	**User 3**	**tr4**	**User 4**	**tr5**	**User 5**	**tr6**	**User 6**	**tr1**
Stim.	Ans.	Stim.	Ans.	Stim.	Ans.	Stim.	Ans.	Stim.	Ans.	Stim.	Ans.
0	a	0	a	0	a	0	v	0	a	0	a
0	a	0	a	0	a	0	a	0	a	0	a
0	a	0	a	0	a	0	a	0	a	0	a
0	a	0	a	0	a	0	a	0	a	0	a
0	a	0	a	0	a	0	a	0	a	0	a
0	a	0	a	0	a	0	a	0	a	0	a
1	a	1	a	1	a	1	v	1	a	1	a
1	a	1	a	1	a	1	a	1	a	1	a
1	a	1	a	1	a	1	a	1	a	1	v
1	a	1	a	1	a	1	a	1	a	1	a
1	a	1	a	1	a	1	a	1	a	1	v
1	a	1	a	1	a	1	a	1	a	1	a
2	a	2	a	2	a	2	a	2	a	2	v
2	a	2	v	2	a	2	v	2	a	2	a
2	a	2	a	2	a	2	v	2	v	2	a
2	a	2	a	2	a	2	a	2	a	2	v
2	a	2	a	2	a	2	v	2	a	2	v
2	a	2	a	2	a	2	a	2	a	2	a
3	a	3	a	3	a	3	a	3	a	3	a
3	a	3	a	3	v	3	v	3	a	3	a
3	a	3	v	3	v	3	v	3	a	3	v
3	v	3	a	3	a	3	a	3	v	3	v
3	a	3	a	3	v	3	a	3	v	3	v
3	a	3	a	3	v	3	a	3	v	3	v
4	v	4	v	4	v	4	v	4	a	4	v
4	v	4	v	4	a	4	a	4	a	4	a
4	a	4	v	4	a	4	a	4	v	4	v
4	a	4	v	4	v	4	a	4	a	4	v
4	a	4	a	4	v	4	v	4	v	4	a

User 1	**tr2**	**User 2**	**tr3**	**User 3**	**tr4**	**User 4**	**tr5**	**User 5**	**tr6**	**User 6**	**tr1**
Stim.	Ans.	Stim.	Ans.	Stim.	Ans.	Stim.	Ans.	Stim.	Ans.	Stim.	Ans.
4	a	4	v	4	a	4	v	4	a	4	v
5	a	5	a	5	v	5	v	5	v	5	v
5	v	5	v	5	v	5	v	5	v	5	a
5	a	5	v	5	v	5	a	5	v	5	v
5	v	5	a	5	a	5	v	5	v	5	v
5	a	5	a	5	v	5	a	5	v	5	v
5	v	5	v	5	v	5	a	5	a	5	v
6	v	6	v	6	v	6	a	6	v	6	v
6	v	6	a	6	v	6	v	6	v	6	v
6	v	6	a	6	a	6	a	6	v	6	v
6	v	6	v	6	v	6	a	6	v	6	a
6	a	6	v	6	v	6	a	6	v	6	v
6	v	6	v	6	v	6	a	6	v	6	a
7	v	7	v	7	v	7	v	7	v	7	v
7	v	7	v	7	v	7	v	7	v	7	v
7	v	7	v	7	v	7	v	7	v	7	v
7	v	7	a	7	v	7	v	7	v	7	v
7	v	7	v	7	v	7	a	7	v	7	v
7	v	7	v	7	v	7	v	7	v	7	v
8	v	8	v	8	v	8	v	8	v	8	v
8	v	8	v	8	v	8	v	8	v	8	v
8	v	8	v	8	v	8	v	8	v	8	v
8	v	8	v	8	v	8	v	8	v	8	v
8	v	8	v	8	v	8	v	8	v	8	a
8	v	8	v	8	v	8	v	8	v	8	v
9	v	9	v	9	v	9	v	9	v	9	v
9	v	9	v	9	v	9	v	9	v	9	v
9	v	9	v	9	v	9	v	9	v	9	v
9	v	9	v	9	v	9	v	9	v	9	v
9	v	9	v	9	v	9	v	9	v	9	v
9	v	9	v	9	v	9	v	9	v	9	v
*	v	*	v	*	v	*	v	*	v	*	v
*	v	*	v	*	v	*	v	*	v	*	v
*	v	*	v	*	v	*	v	*	v	*	v
*	v	*	v	*	v	*	v	*	v	*	v
*	v	*	v	*	v	*	v	*	v	*	v
*	v	*	v	*	v	*	a	*	v	*	v