Tactile Perception of Spatially Distributed Vibratory Stimuli on the Fingerpad

By

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Abstract

Using a pin-array type tactile display as a stimulator of the finger pad, a psychophysical study was conducted on the vibrotactile perception. The passive touch with vibratory stimuli in the low frequency could be an alternative of the active touch for the presented stimuli: polygons, round shapes and gratings. As for the effect of frequency on the texture discrimination, the high correct answer proportions corresponded to the most sensitive frequency ranges of each mechanoreceptor. The spatial acuity decreased as the frequency of the stimuli increased when the stimuli presented by the equal number of contactors.

As an analogy between color vision and tactile perception, a spatial configuration of the multiple contactors was proposed to deliver the intermediate pitch using the compound waveform defined as a sinusoidal stimulus which was presented by four contactors vibrating with 30Hz and 240Hz. The subjects felt qualitatively different the compound waveform and the pure-tone. When the high frequency component had 3 times the intensity of the other component, the perceived frequency of the compound waveform was about 120Hz which was much lower than the component frequency 240Hz. The experimental results were explained by the hypothesis of a ratio code, neural mechanism signaling the frequency of vibratory stimuli based on the ratio of the one-to-one activated population of mechanoreceptors. In addition, the intensity of the components also affected the overall perceived frequency.

Thesis Supervisor: Dr. Mandayam A. Srinivasan

Title: Senior Research Scientist, Department of Mechanical Engineering

Acknowledgements

First of all, I would like to thank my God who always loves me and leads my whole life.

"Have I not commanded you? Be strong and courageous. Do not be terrified; do not be discouraged, for the LORD your God will be with you wherever you go." (Joshua 1:9)

I thank my advisor Dr. Mandayam A. Srinivasan who gave me the opportunity to work in the Touch Lab and tolerated my research wanderings. My deepest thanks go to Dr. David Schloerb for his guidance throughout the projects. Dr. James Biggs helped me with many technical problems. I am particularly thankful to Hyun Kim for his ever-willingness to cheer me up. I would also like to thank Ki-Uk Kyoung with whom I collaborated on development of the tactile display. Thank all others who worked with me in the Touch Lab.

I want to thank my parents for their lifetime of love, care and support.

Lastly, I would like to thank my wife, Minyoung. Without her love, support and sacrifice, I could never have finished this thesis.

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1 Introduction

1.1 Cutaneous Sensation and Tactile Feedback

A variety of devices for giving force and tactile feedback have been developed in an attempt to mimic touch in virtual environments. Although force feedback devices that simulate contact at one point are widely used [1], the development of realistic tactile displays is still in an early stage due to the lack of appropriate actuators and methodology needed to stimulate human skin in a life-like manner. Tactile sensations result from the stimulation of mechanoreceptors in the skin [2]. Various types of touch receptors have been identified, each with their own characteristics and functions, as summarized in Table 1-1. Bolanowski *et al.* (1988) proposed four psychophysical channels mediating unitary sensation from a specific end organ or mechanoreceptor [3]. Figure 1.1 represents the structure of hairless skin and the mechanoreceptors underneath the fingertip.

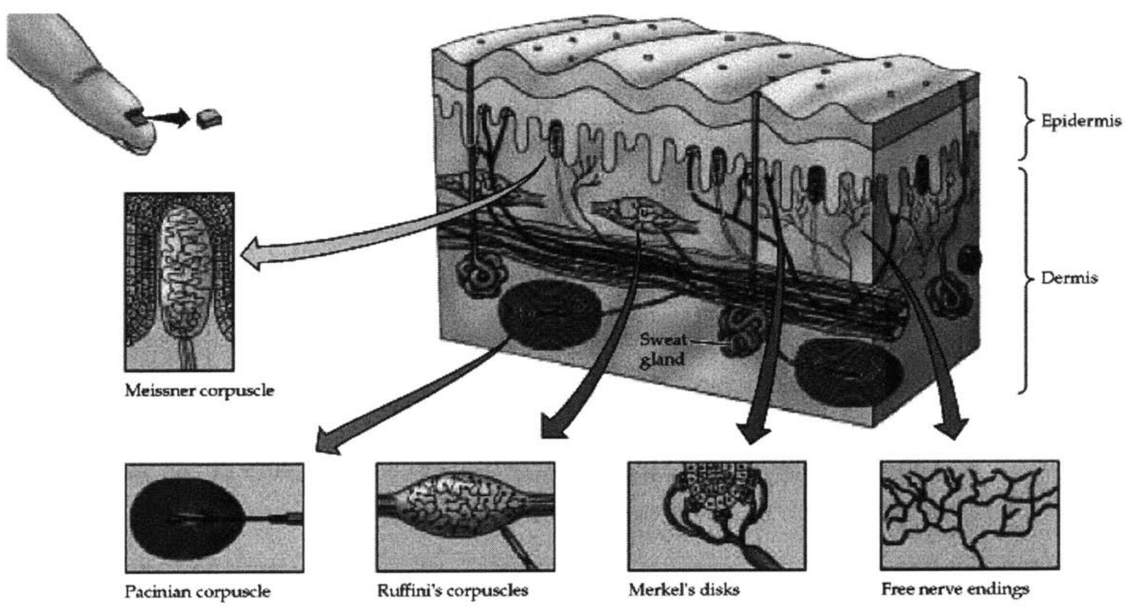


Figure 1.1 The structure and location of mechanoreceptors in the glabrous skin [2, 4]

Mechanical stimulation of the touch receptors in the skin triggers a response in the corresponding nerve fibers. This response, which is a kind of electrical discharge ("action potential"), is transmitted to the somatosensory cortex through a chain of neurons [5]. In order to understand how tactile sensations are encoded, we need to observe the afferent neural signals which result from various types of tactile stimuli. This is difficult to do, however, particularly in the case of spatially distributed stimuli which might depend on the population behavior of the multiple neurons [6]. This thesis investigates the effect of frequency and intensity on the perception of planar distributed tactile stimuli using psychophysical methods.

Receptor type	Merkel disks	Ruffini endings	Meissner corpuscles	Pacinian corpuscles
Sensation quality	Pressure	Stretching of skin	Tap, flutter	Vibration
Density(per cm^2) at finger tip	70	49	140	21
Best frequency range	0.4-1Hz	150-400Hz	25-40Hz	250-300Hz
Receptive field size	Small	Large	Small	Large
Adaptation property	Slow	Slow	Rapid	Rapid
Psychophysical channel	NP III channel	NP II channel	NPI channel	P channel

Table 1-1 Summary of the property of mechanoreceptors [4, 7]

1.2 Vibrotaction and neural codes

How people encode and interpret the information from a vibrotactile stimulus has been an interesting subject in neuroscience and psychophysics for a long time. Talbot *et al.* (1968) compared the human responses to vibratory stimuli with the neural signals from the afferents of the monkey hand [8]. Mountcastle *et al.* (1969) extracted the cortical signals for vibratory stimuli from the monkey brain [9]. They divided the vibrotactile sensation into "flutter" and "vibration", and tried to elucidate the mechanism for signaling the frequency and amplitude at the afferent and cortical levels. The major candidate for frequency encoding mechanism is an impulse or temporal pattern code in which the phase-locked neural signals transmit the frequency information. This hypothesis is supported by the fact that many types of afferents neurons fire according to the frequency of the sinusoidal stimulus [6, 8, 10]. A weakness of the temporal code is that the phase-locking tends to weaker as the neural signals travel from the peripheral to the cortex [11].

An alternative view of interpreting the code of vibrotactile pitch, the perceptual quantity associated with the frequency of vibratory stimuli, is a ratio code based on the relative activation of different mechanoreceptors [6, 11, 12]. Because the psychophysical channels for producing tactile sensation have different sensitivity to vibratory stimuli, this ratio code seems to be possible. Morley and Rowe (1990) investigated the perceived pitch with changes in amplitude for two stimuli of 30Hz and 150Hz in order to vary the ratio of recruitment of PC (Pacinian corpuscle-associated) and RA (Rapidly adapting) fibers [6]. They hypothesized the ratio code of pitch, and predicted a significant decline in pitch at 150Hz as the stimulating amplitude increased. Their experimental results, however, were different from subject to subject at both frequencies. In fact, five of eight subjects reported an increase in pitch as the amplitude of 150Hz stimulus increased while only two experienced a decrease in pitch which was expected based on their prediction. Morley and Rowe, therefore, concluded that the ratio code hypothesis couldn't support the experimental results and the temporal impulse pattern code was still a major candidate for signaling the pitch.

Horch (1991) focused on the encoding of vibrotactile stimulus frequency in the range of Pacinian corpuscle-associated. He asked the subjects to discriminate between pure-tone stimuli at 120Hz and diharmonic stimuli that has 120Hz fundamental with a second harmonic component half the amplitude of the fundamental. The subjects matched the diharmonic stimulus to a 168Hz pure tone, which is the harmonic mean of the fundamental (120Hz) and harmonic components (240Hz). This result could support the population response model which predicted the perceived pitch as the inverse of the mean interval of individual activation. In this model, half the Pacinian corpuscles were responding to the harmonic component while the others only were entrained by the fundamental component, which happened with equal probability. In addition, he predicted that people should confuse amplitude with stimulus frequency, which might be tested by dual stimulators [13].

Recently Roy and Hollins proposed a modification of the ratio code for vibrotactile pitch based on the ratio of PC activity to the sum of P, NPI, and NPII channels. They estimated the activity level using loudness which was defined as a function of stimulus amplitude, sensitivity of each channel at a given frequency, and individual scale factors. Although they also agreed with some inconsistency across subjects in the trend of the perceived pitch as the stimulus amplitude changed, he pursued the modified ratio code model by which the pitch estimated was well described for the normal three subjects [11].

The ratio code in vibrotactile perception might be analogous to the human color vision system which depends on the cone photoreceptors with different spectral sensitivities [14]. Using this wavelength selectivity of the cone cells, various colors in computer graphics can be produced by changing the intensity of only three primary colors: Red, Green and Blue (RGB). Similarly, if there are primary tactual elements in the human haptic system, like RGB in computer graphics, the design of vibrotactile displays would be much simpler than with existing approaches which stimulate the skin using actuators capable of vibrating over the whole range of frequency. This tactile color methodology might make it possible to design tactile displays more effectively and at low cost.

In spite of all these effort to elucidate the encoding of vibrotactile frequency, there is little attempt so far to test the ratio code using multiple stimulators presenting spatially distributed stimulus. The present study used a tactile display which can provide planar distributed vibratory stimuli using multiple contactors in the broad range of frequency.

1.3 Organization of thesis

Chapter 1 presents a brief introduction to cutaneous sensation and tactile displays.

Chapter 2 describes the specification of the tactile display used in the thesis experiments. The development of the experimental software and the generation of sinusoidal stimuli are also discussed.

Chapter 3 describes two psychophysical experiments designed to investigate the effect of frequency on the identification of planar figures. The ability of discrimination depended on the active mechanoreceptor groups and overall power levels.

Chapter 4 presents two experiments designed to test whether compound tactile stimuli consisting of two discrete frequencies might be perceived as a single intermediate frequency. This was done in order to investigate the possibility of developing a tactile display based on tactile color. The two frequencies used corresponded to the best frequencies of two mechanoreceptor groups--Meissner (RA) and Pacinian (PC)--and the compound stimulus was varied by changing the power ratio of the two frequencies. The experimental procedures were based on the methods of adjustment and same-different paradigm.

Chapter 5 describes the analysis of the experimental results and two follow-up experiments. A model for explaining the response trends is proposed in the discussion section.

Chapter 6 summarizes and concludes the present work.

2 Experimental Apparatus and Software

We have developed a tactile display to present texture patterns to human users [15]. The design of the hardware is not the focus of this thesis, so in this chapter I describe the specification of the device, how it works and the development of the operating software. The tactile display system was used for all of the psychophysical experiments described in this thesis.

2.1 Specification of the tactile display

The pin-array type tactile display is composed of a 6×5 pin array actuated by 30 piezoelectric bimorphs. The pins lie on 1.8 mm centers. The vertical excursion of each pin is controlled over a 0-700μm range. The tip of the contactors is hemispherical with a diameter of 0.7mm. Table 2-1 shows the detail of the important specification of the tactile display.

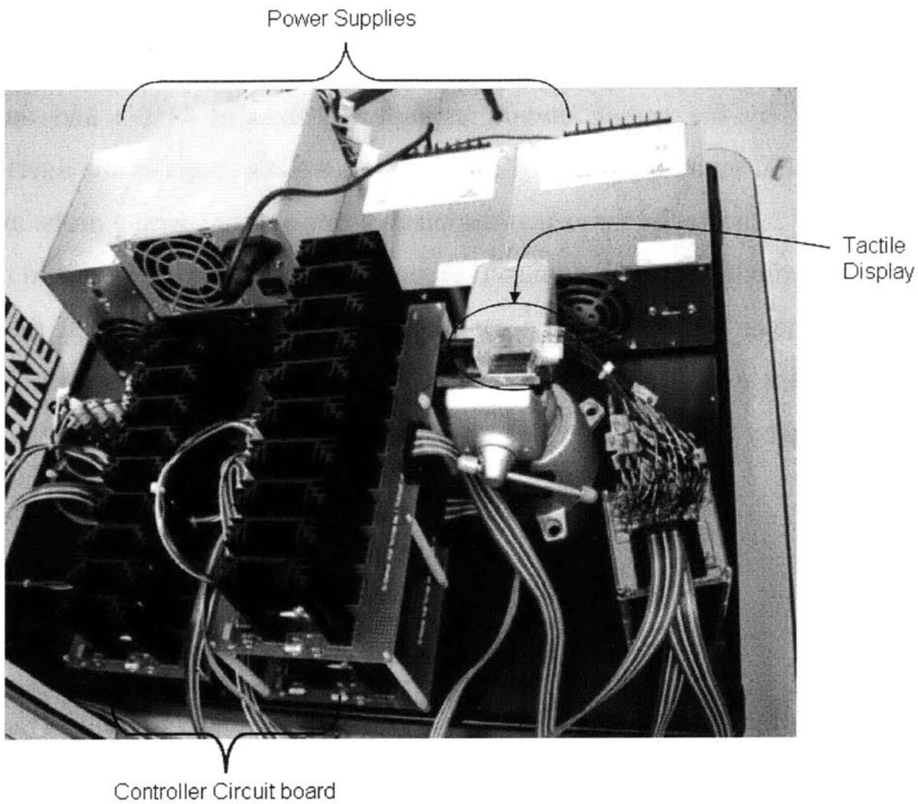
Number of contactors	30	Bandwidth	325Hz
Diameter of a contactor	0.7mm	Resonance frequency	250Hz
Spatial resolution	1.8mm	Supply Voltage	168V,±15V,-48V
Resolution of normal deflection	0.16μm	Cooling	Air/Fan
Maximum deflection	>700μm	Blocking Force[1]	>0.06N
Compliance of the actuator	10.73mm/N	Capacitance	12,000pF

Table 2-1 Summary of device specifications

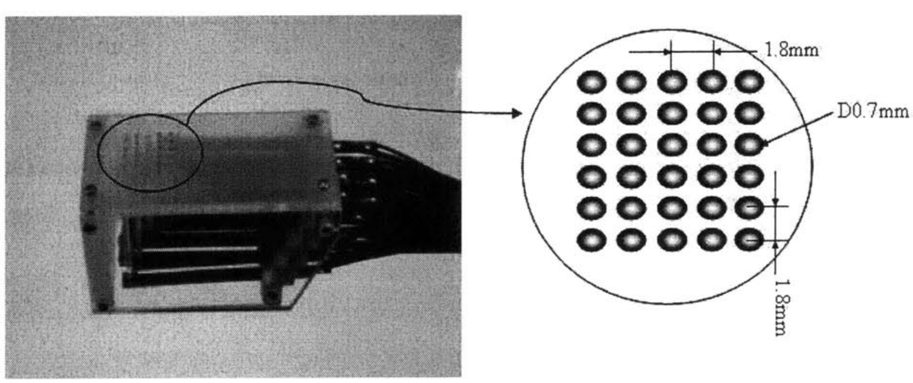
Figure 2.1(a) shows the whole system including power supplies, control circuits and the array of contactors. The control circuit is connected to Pentium4 computer (CPU 3.6GHz) by a D/A card (PCI-6723, National Instruments) mounted in the computer. The tactile array itself is small enough (40mm×23mm×20mm) to be portable and easily

[1] Blocking force = [deflection]/[compliance]

attached to other devices. In the present experiments, it was mounted in a way to make the subjects comfortable and to reduce noise.



(a) Top view the whole experimental device



(b) Close-up of the tactile display

Figure 2.1 The Tactile Display and the top view of its interface with a finger tip

A closer view of the direct interface to the skin is shown in the Figure 2.1(b). The diameter of holes coaxial with the probes on the upper plate is 1.1mm, so the gap between a probe and the surrounding is 0.2mm. The normal deflection and the frequency of each probe can be controlled individually with a resolution of 0.16μm in the bandwidth which was calculated[1] by the analog output resolution (13bits in ±10V) and the frequency response. For a DC input, the tactile display presents a static shape on the interface window.

Figure 2.2 shows the frequency response of one actuator with a probe attached. The response, approximately that of a damped second order system, was measured using a laser Doppler vibrometer (OFV511, Polytec). The maximum displacement of the actuator is relatively constant at 0.067mm/V over the range 0-100 Hz. Damped resonance is evident at 250Hz, followed by roll-off [15].

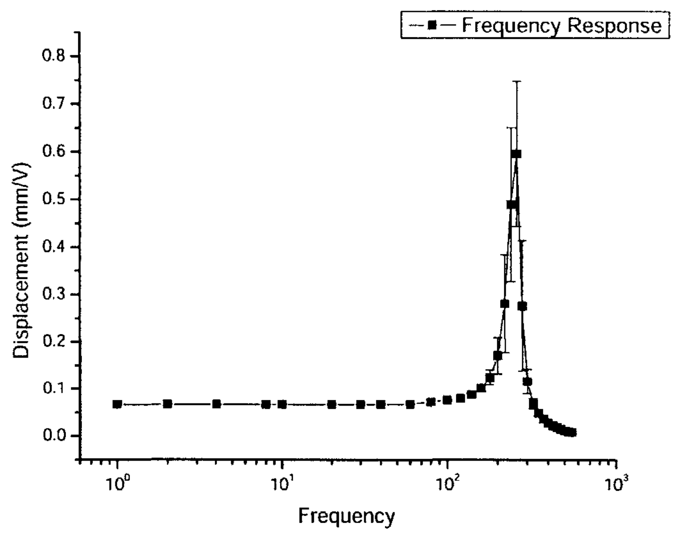


Figure 2.2 Frequency response of a single actuator with a probe mounted

[1] normal deflection resolution = $20/2^{13} \times 0.067$ mm

2.2 Software Design for operating the tactile display

2.2.1 Development Environment

When it comes to the software development environment, interchangeability is important in order to make it easier to use the tactile display with other systems like kinesthetic feedback devices. One haptic display device developed previously, the PHANToM (SensAble Technologies), has been used to prototype a wide range of force-based haptic display primitives. The GHOST SDK library provided for programming the PHANToM is in the C++ language. I selected Visual C++ for software development in the present project and used MFC (Microsoft Foundation Class) to help implement a graphical user interface (GUI).

2.2.2 Implementation

In order to make user friendly software, I implemented programs with a dialog window in which events (e.g., a button press) call the corresponding function. For generating analog waveforms, I used the NI-DAQmx C++ library (National Instruments). The flowchart in Figure 2.3 shows the general procedure of the program.

When a dialog window is opened, the DAQ (data acquisition on the D/A card) is also initialized for setup of the sampling rate, clock modes and the task channels. The initializing functions below were put into the function OnInitDialog() in the dialog class.

- *DAQmxCreateAOVoltageChan(taskHandle,chan,"",min,max,DAQmx_Val_Volts,NULL);*

The *chan* term was set to "Dev1/ao0:29" as a global variable for channel setting, which activated 30 analog output channels from 0 to 29 in device 1 (the D/A card). The minimum (*min*) and maximum (*max*) of the voltage were set to ±10V.

- *DAQmxCfgSampClkTiming(taskHandle,NULL,rate,DAQmx_Val_Rising,DAQmx_Val_FiniteSamps,1000);*

This function enables the hardware timing and control of stimulus duration. The second argument was set to *NULL* to use the onboard clock. The *rate* term and the last term for the number of samples per channel determined the stimulus duration. For instance, if the *rate* is 1 kHz and the number of samples per channel is 1000, the signal duration is one second

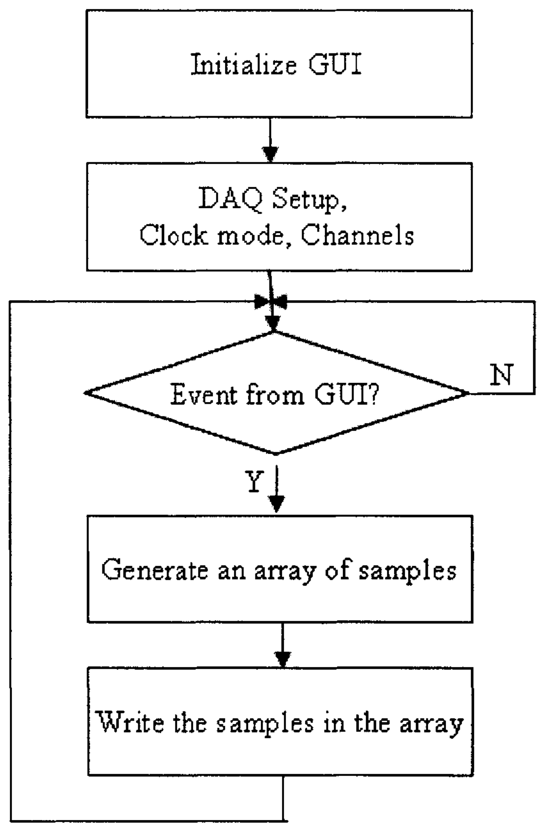


Figure 2.3 Generation of Analog Output Flowchart

After initialization, the program waits for an event in the GUI. When an event occurs in the GUI, such as clicking a button for choosing a shape or editing the value of the frequency or displacement, an array of samples is generated corresponding to the event.

The arrays of the amplitude and the frequency are transmitted as the arguments of the update function for activating the probes. Figure 2.4 is a pseudo-code for generating the stimulus. The sine waveform was generated by the discrete sampling of N Hz.

$$data[j] = \frac{1}{2} A[i] \left\{ 1 + \sin(2\pi \cdot freq[i] \frac{j}{N}) \right\} \tag{2.1}$$

,where i=0,1,2 … ,29 channel, j= j^{th} sample($0 \le j < 30*N$)

N= number of samples per channel

A[i]= amplitude in Volts, freq[i]=frequency in Hz

Using the Equation(2.1), I allocated N samples to each channel according to the designated frequencies and amplitudes as follows.

```
for(i=29;i>=0;i--)
{
        if(Freqs[i]==0.0)
        {
                for(;j<(30-i)*N;j++)
                  data[j]=volts[i]*1.0;
        }
        else
         for(;j<(30-i)*N;j++)
          {
                data[j]=volts[i]/2*sin(2*PI*Freqs[i]*j/N)+volts[i]/2;

          }

}
```

$$
Amplitude = \begin{pmatrix} a_1 & a_2 & \cdots & a_6 \\ a_7 & a_8 & \cdots & a_{12} \\ \vdots & \vdots & \vdots & \vdots \\ a_{25} & a_{26} & \cdots & a_{30} \end{pmatrix};
$$

$$
Freqeuncy = \begin{pmatrix} f_1 & f_2 & \cdots & f_6 \\ f_7 & f_8 & \cdots & f_{12} \\ \vdots & \vdots & \vdots & \vdots \\ f_{25} & f_{26} & \cdots & f_{30} \end{pmatrix};
$$

```
Update_Pin(Amplitude, Freqeuncy)
{
voltage = convert_to_voltage(Amplitude);
samples = generate_signal(voltage, Freqeuncy);
write(samples);
}
```

Figure 2.4 Pseudo-Code describing patterns

Using the generated array of samples, the simultaneous update of the individual probes is implemented as follows.

DAQmxWriteAnalogF64(taskHandle,N,autoStart,timeout,DAQmx_Val_GroupByChannel,data,NULL,NULL);

The second argument *N* is the number of samples per channel to write. Because the one dimensional data array is organized in a non-interleaved fashion, data layout is set to "*DAQmx_Val_GroupByChannel*". Non-interleaved samples prioritize channels before samples, such that the array lists all samples from the first channel in the task, then all samples from the second channel, up to all samples from the last channel (NI-DAQ™mx C Reference).

2.2.3 Example: Control software for individual pin activation

In order to use the tactile display for psychophysical experiments or other virtual reality applications, we need a test program which enables us to feel the sample patterns in advance and to modify the experimental procedures. The test program is also necessary for operational testing of the hardware. Figure 2.5 is the graphical user interface of the test program which controls the individual input voltages to the amplifying circuit and the frequency of sinusoids. The displacement of each pin is calculated based on the frequency response of a single actuator (see Figure 2.2), which is 0.067mm/V in the air until the resonance.

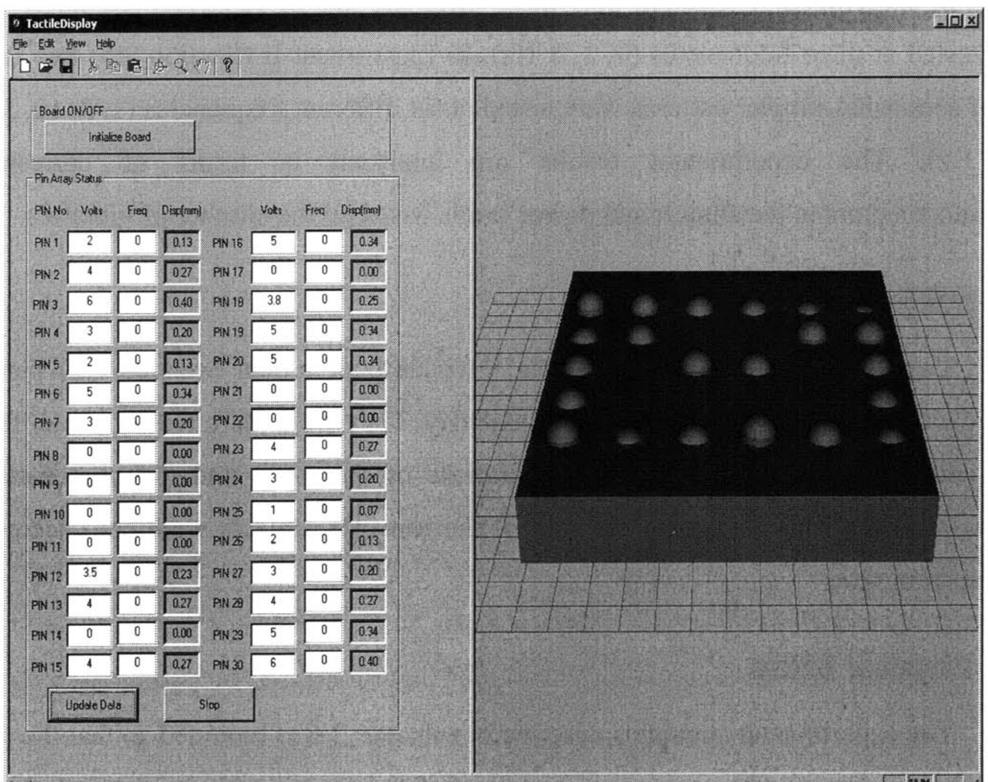


Figure 2.5 GUI for control of the tactile display. A user edits the amplitude (V) and frequency (Hz) of the individual pins in the edit boxes. The button "Update Data" in the left bottom of the window updates all 30 pins simultaneously. The maximum deflections of the activated pins are shown in the right graphic window.

3 Perception of Uniform Sinusoidal Stimuli

Two psychophysical experiments were performed to study the affect of frequency on the identification of uniform planar textures under conditions of passive touch. In all cases the subjects were instructed to simply place their fingers passively on the tactile display and not stroke it or otherwise actively explore the texture being presented. During a trial, the texture was either static or it vibrated in a sinusoidal motion perpendicular to the plane of the display and the surface of the subject's finger pad. The subject's task was to identify which pattern out of a given set of patterns was presented.

In Experiment I (Section 3.4) three different sets of relatively complex patterns were tested at three frequencies (0, 1, 3 Hz). In Experiment II (Section 3.5) two different sets of somewhat simpler patterns were tested at six different frequencies (1, 3, 10, 32, 100, 250 Hz). The experimental results are analyzed in terms of corresponding mechanoreceptors to the stimuli and power levels based on the number of vibrators.

3.1 Subjects

Twenty-two naive subjects (13 men, 9 women), all in their twenties, each performed both identification tests (I and II) on the same day. They were recruited by e-mail from the MIT community or acquaintances. The purpose of the study and the procedures were explained to the subjects before the start of the test. All subjects were paid according to participation time.

3.2 Physical Setup

The experimental apparatus described in chapter 2 was mounted so that the subjects would be comfortable. The subjects sat in front of the display with their right index finger on the tactile display interface. Noise blocking earmuffs (Viking, Bilsom) were used in order to minimize the effect of the mechanical noise. The computer monitor was turned away from the subjects so that they could not see it during tests and the experimenter used the GUI[1] (shown in Figure 3.2 or Figure 3.7) to run the experiment.

3.3 Stimulus

In both experiments, textures were created by activating specific subsets of the pins on the tactile display so that they were raised above the other (inactive) pins. The inactive pins all remained at the zero position, nominally at the surface of the skin. The active contactors, which formed the pattern, were all raised to the same height above the inactive contactors and, in the case of a vibratory stimulus, the tips of the active pins moved together in a plane. Note that because the subject's finger was only passively placed against the pins, the finger pad did not have appreciable shear deformation.

Sinusoidal stimuli were generated with a 5 kHz sampling rate according to equation 3.1. The sinusoid was shifted upward by one-half the stimulus amplitude so that the tips of the active pins were always above the nominal zero position; in other words, so that they were always nominally indented into the skin.

$$Stimulus = \frac{1}{2} A \sin(2\pi f \times \frac{i}{5000}) + \frac{1}{2} A \qquad (3.1)$$

where A = amplitude of the stimulus (peak to peak)

f = frequency of the stimulus

i = iteration number

Figure 3.1 shows the shifted sinusoidal stimulus when the amplitude is the maximum deflection (0.7mm) of the bimorph and the frequency is 3Hz. Note that the stimulus duration was always 10 seconds and that the contactors stepped into the skin by a distance equal to 1/2 A at t = 0 and, then, stepped back out to the nominal skin surface position at t = 10. In the case of a "static" stimulus the amplitude was adjusted so that the contactors stepped in by A. The ramp speed of the step was approximately over 70 mm/sec

[1] GUI: Graphical User Interface

based on the fact that typical response time of piezoelectric bimorphs is in the millisecond range.

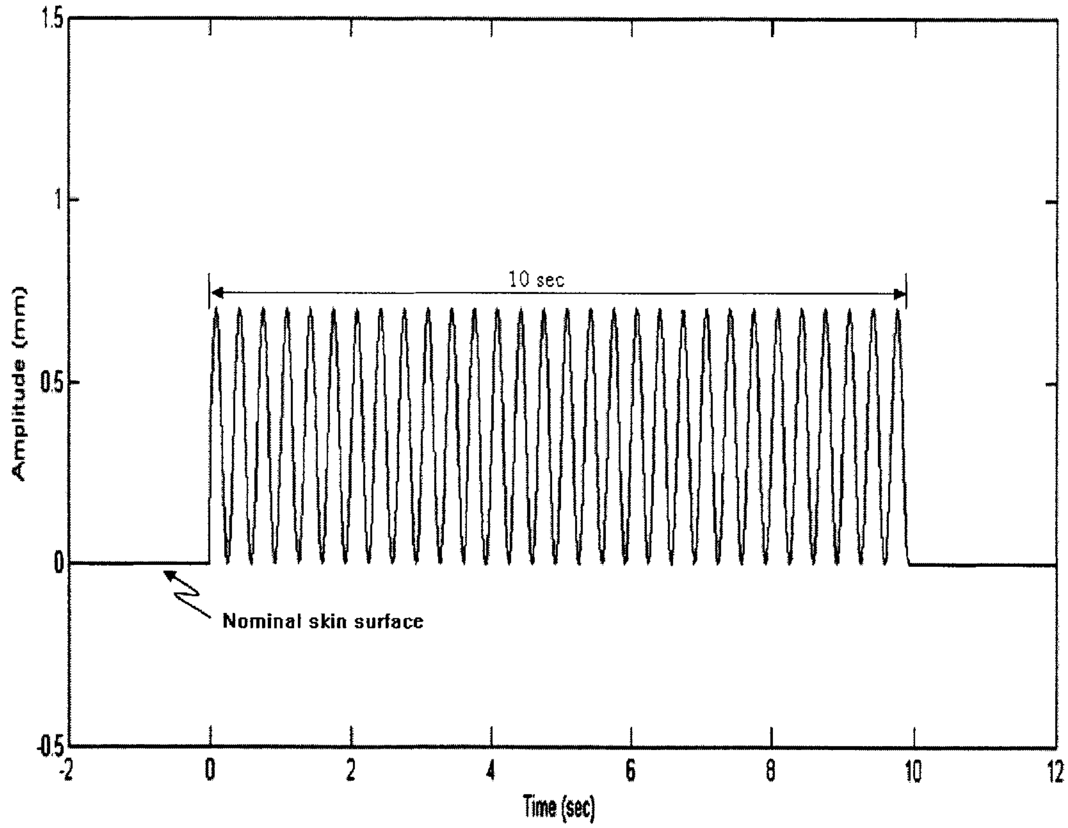


Figure 3.1 Sinusoidal Stimulus (A=0.7mm and f=3Hz)

3.4 Experiment I: Pattern Identification 0-3Hz

In this Section, we investigate how vibrotaction, particularly in low frequencies that have identical thresholds, affects the identification of forms with only passive touch.

3.4.1 Methods

When presented with the tactile stimulus, the subject was asked which shape in a photo copy of the GUI (Figure 3.2) was the most similar to the feeling on his/her finger tip. The stimulus lasted for 10 seconds, but they usually answered in 3-4 seconds. The experiment was divided into 3 parts corresponding to the 3 different sets of tactile patterns, or texture groups, that were presented: polygonal shapes, round shapes, and gratings (Figure 3.3-Figure 3.5). Each of the 3 texture groups was presented at 3 different frequencies: static, 1Hz and 3Hz. Within each texture group, separate trial runs were performed at each frequency in order with 5 minutes rest after each frequency run and between each texture group. The input voltage corresponding to the stimulus amplitude (A in equation(3.1)) was 7.5V for all of the stimuli, corresponding to a 0.5mm deflection of the actuator in air. Correct answer feedback was not given in the experiment.

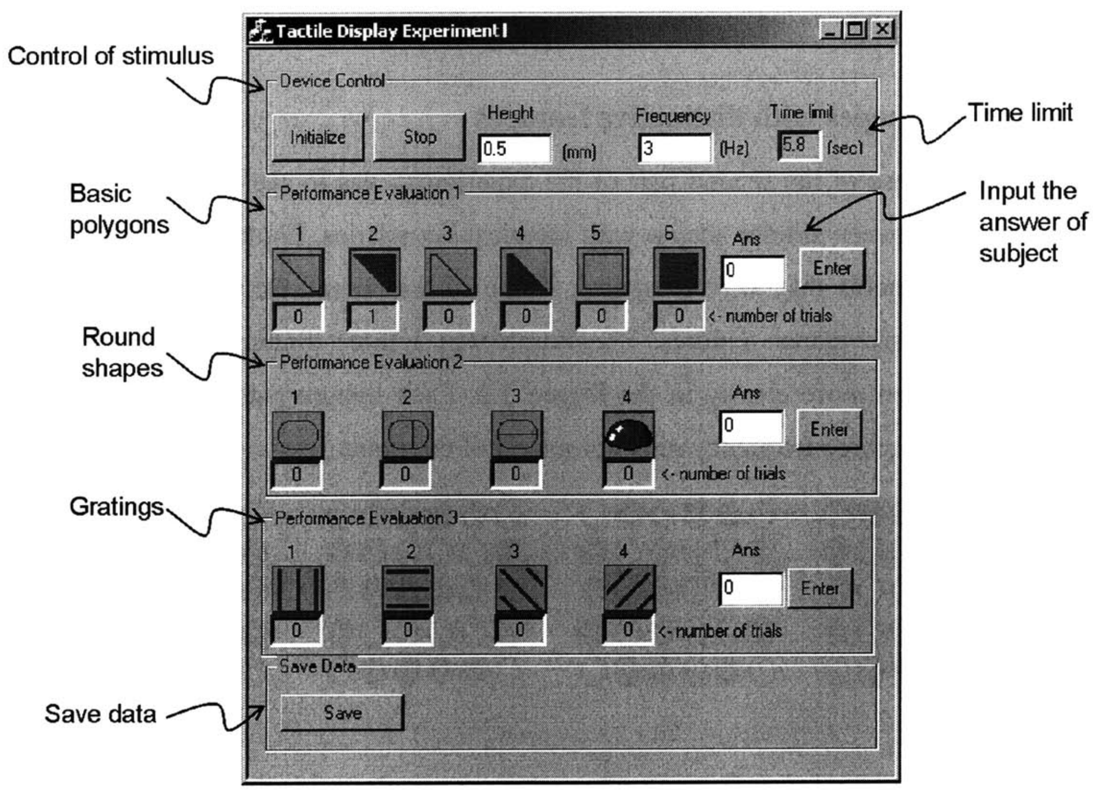


Figure 3.2 GUI of the experiment for pattern detection in low frequency

3.4.2 Polygonal shapes

Figure 3.3 shows the 6 test patterns consisting of blank and filled polygonal outlines that were used in the first part of the experiment. Each texture pattern was displayed 5 times randomly, for a total of 30 trials at each of the 3 frequencies.

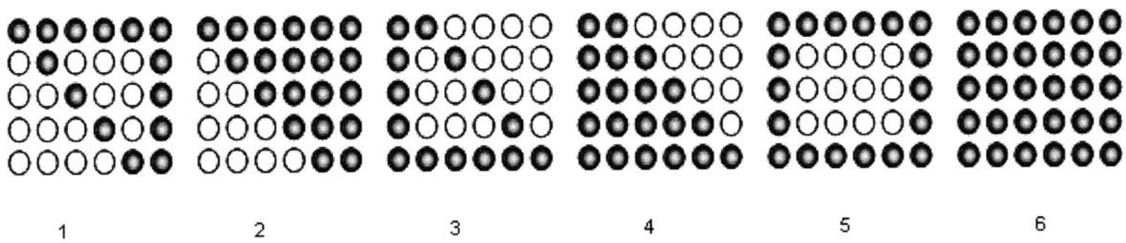


Figure 3.3 Planar polygonal patterns

3.4.3 Round shapes with distinctive features

The purpose of the second part of the experiment was to see how the subjects tell the difference between similar shapes with identical boundaries. Figure 3.4 shows the four round texture patterns that were presented. Three of the stimuli (left three shapes in the figure) were simple planar textures. The fourth was a three dimensional half ellipsoid, which can be seen more clearly in the Figure 3.2. Each texture pattern was displayed 5 times randomly in three frequency runs, for a total of 60 trials.

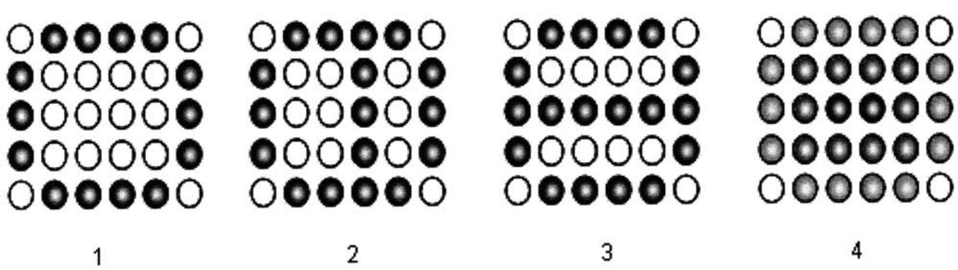


Figure 3.4 Round shape samples

3.4.4 Gratings

Figure 3.5 shows the four grating patterns used in the last part of the experiment. The purpose of this test was to see how well the tactile display could present gratings and their directions. Each texture pattern was displayed 5 times randomly in three frequency runs, for a total of 60 trials.

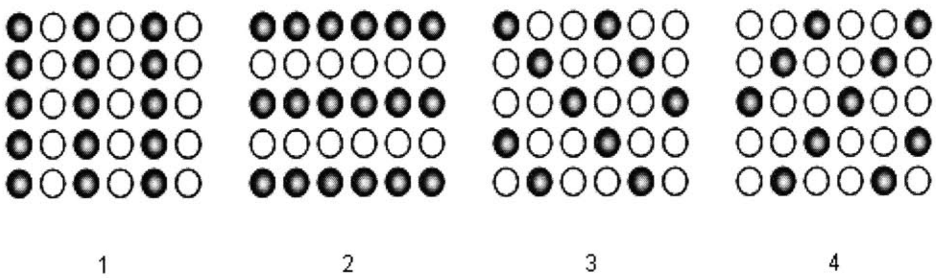
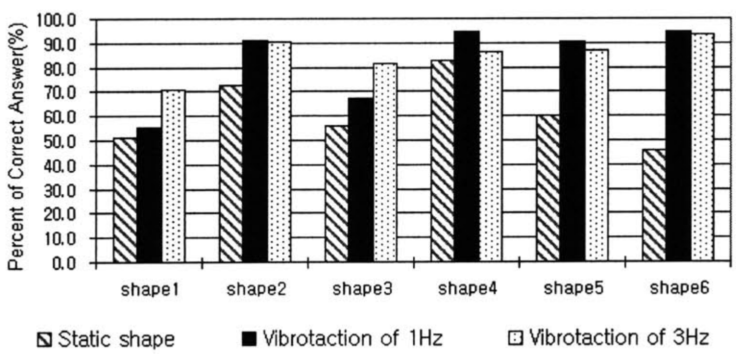


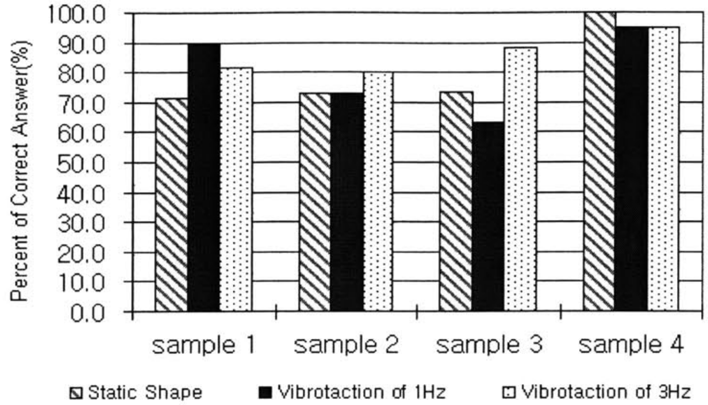
Figure 3.5 Grating patterns

3.4.5 Results and Discussion

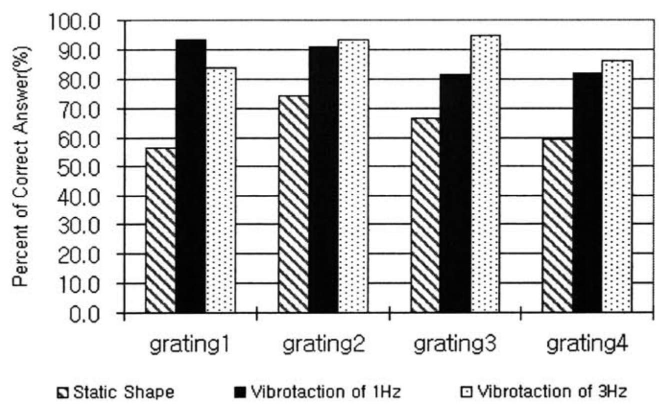
The average correct answer rates for all 22 subjects in the experiment are presented in the Figure 3.6, for each shape group and frequency. The figure shows that the proportion of correct answers generally increases as the stimulating frequency rises from static to 1 Hz to 3Hz. The proportion of correct answers at 3Hz was around 90%. This suggests that passive touch with low frequency vibration may be a viable alternative to active touch, because in a previous experiment we did with the same (static) stimuli under active touch conditions, the proportion of correct answers was 90-99% depending on the stimulus [15].



(a) The percent of correct answers for 6 polygonal shapes



(b) The percent of correct answers for rounded shapes



(c) The percent of correct answers for gratings shape

Figure 3.6 Small scale shape discrimination at low frequency

According to Bolanowski *et al.* (1988), there are four psychophysical channels in the glabrous skin which consist of specific end organs or mechanoreceptors: Pacinian corpuscles, Meissner corpuscles, Ruffini endings and Merkel's disks. Each channel respectively has the most sensitive frequency. For example, P channel[1] produces the sensation of "vibration" in the frequency range of 250-300Hz. The best frequency of NPI

[1]P: Pacinian

channel[1] is 25-40Hz. NPIII channel mediated by Merkel's disks transmits the sensation of "pressure" in the frequency range of 0.4-2.0Hz [3]. In our experimental results, it seems likely that 1-3Hz vibration is effective at stimulating the Merkel's disks and that the associated SAI afferents provide the fine spatial resolution necessary to make the discriminations.

3.5 Experiment II: Pattern Identification 1-250Hz

The results of section 3.4 suggest that the sensitivity of passive touch was improved by increasing vibration frequency over the 0-3Hz range. This section focuses on discrimination of tactile forms over a broader frequency range to see if the trend continues at higher frequencies.

3.5.1 Methods

When presented with the tactile stimulus, the subject was asked which shape in a photo copy of the GUI (Figure 3.7) was the most similar to the feeling on his/her finger tip. The stimulus lasted for 10 seconds, but they usually answered in 3-4 seconds. The experiment was divided into two tests. Each test involved a different group of texture patterns (Figure 3.8 and Figure 3.11) which were presented at 6 different frequencies: 1, 3, 10, 32, 100 and 250 Hz. For each test, the 6 frequencies were tested in separate trial runs with 5 minute rest after each run and between the two tests. Correct answer feedback was not given in the experiment.

When testing subjects with vibratory stimuli, it is desirable to compensate for high sensitivity around 250 Hz. This can be accomplished using contours of constant perception intensity. In a previous test we measured the vibratory sensation thresholds of the index finger pad using the same tactile display and a laser Doppler vibrometer [16]. In the following experiment, we attempted to adjust the amplitude of the stimulus (A in equation(3.1)) to be around 32 dB above the observed thresholds. However, the actual

---

[1]NP: non-Pacinian

displacement of the skin may have been different from the calculated value, which was based on the frequency response of the actuators with no load (Figure 2.2), such that the real stimulus level may have been lower than 32 dBSL. The input data are summarized in Table 3-1.

Frequency(Hz)	Threshold (μm)	Displacement (μm)	dBSL	Voltage (V)
1	9.484	400	32.5	5.97
3	9.595	400	32.4	5.97
10	10.305	400	31.7	5.97
32	5.11	200	31.8	2.99
100	3.34	130	31.8	1.94
250	2.145	85	32.0	1.27

Table 3-1 Amplitudes of the stimuli at each frequency derived from previously measured tactile thresholds [16]. The displacement amplitudes are presented in terms of the input voltage to the tactile stimulator, in addition to units of μm and dBSL, because of uncertainties in our calculation of the actual displacement of the skin.

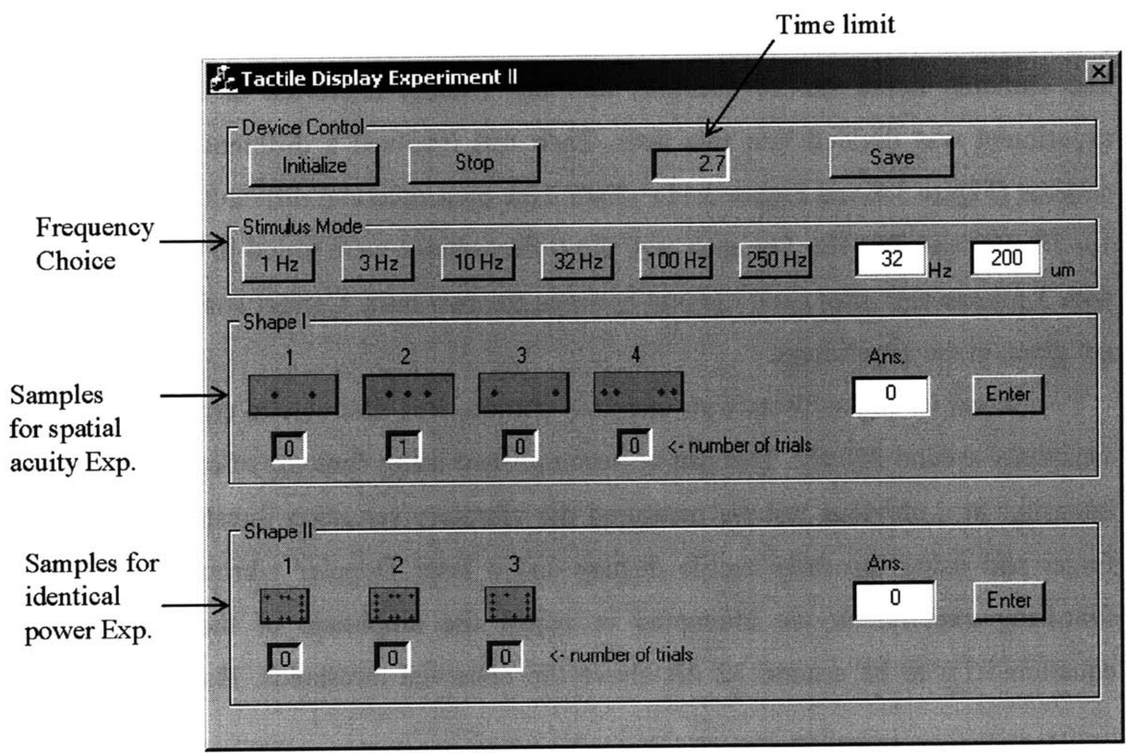


Figure 3.7 GUI for Experiment on effects of frequency

3.5.2 Spatial acuity

Varying the distance between two points and the number of contactors, we could investigate the effect of frequency and power level on the special acuity. Figure 3.8 shows the 4 stimuli asked to discriminate. The first stimulus is activation of two pins separated by a space. The second stimulus is activation of three adjacent pins. The third stimulus is similar to the first but there are two empty spaces between active pins. The last stimulus has 4 pins activated with one blank in the middle.

Each texture pattern was displayed 5 times randomly at 6 frequencies, for a total of 120 trials.

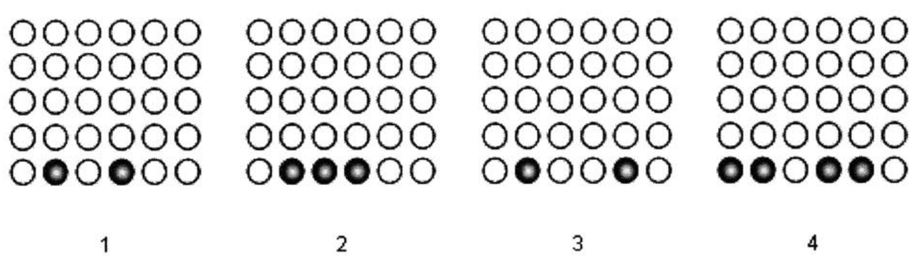
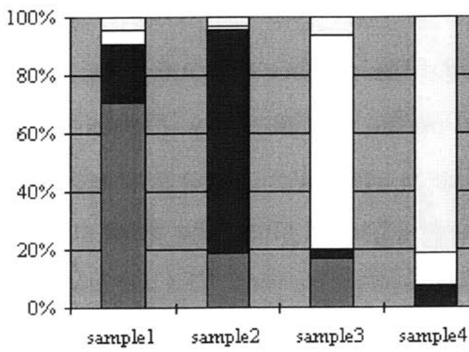
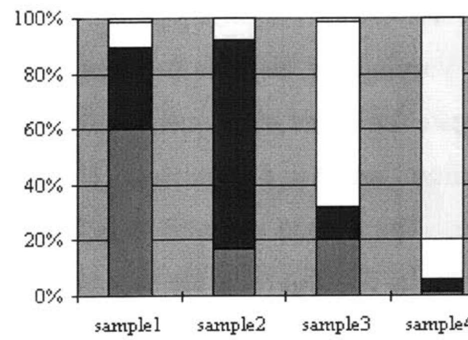


Figure 3.8 Samples for spatial acuity experiment

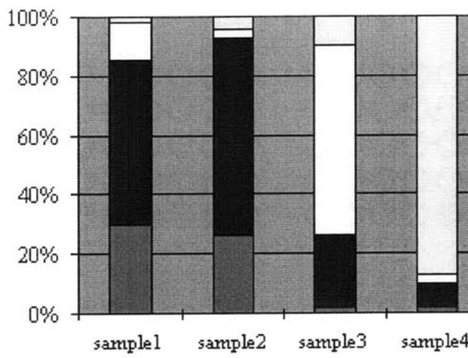
Figure 3.9 shows the graphs of the confusion matrices which consist of stimuli presented and responses of the subjects. The confusion trend of the subjects can be read by comparing the area of the bar graph. The results show that the subjects were very confused in discriminating between sample 1 and sample 2, and between sample 1 and sample 3 at frequency of 10, 100 and 250Hz. Figure 3.10 summarizes the overall proportion of correct answers. In general, higher frequency stimulation made subjects worse at discriminating the stimuli. The subjects generally did better at low frequencies (1-3 Hz) than at higher frequencies (10-250 Hz). It should be noted that the minimum percentage of correct answers occurred around 10Hz and that the correct percentage slowly increases as the frequency rises up to 32Hz which is a local maximum. Another unexpected result was that at 250Hz, the percentage of correct answers slightly increases again.



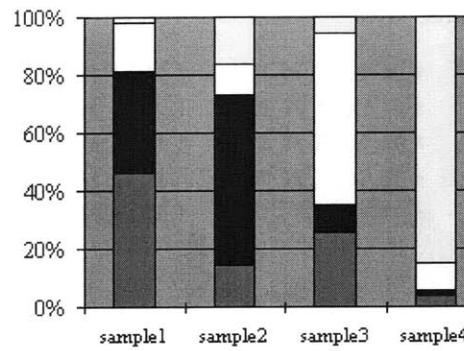
(a) Rate of Confusion at 1Hz



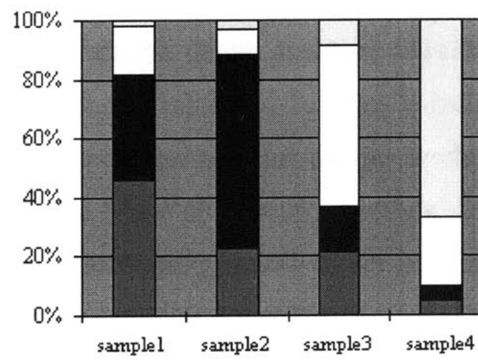
(b) Rate of Confution at 3 Hz



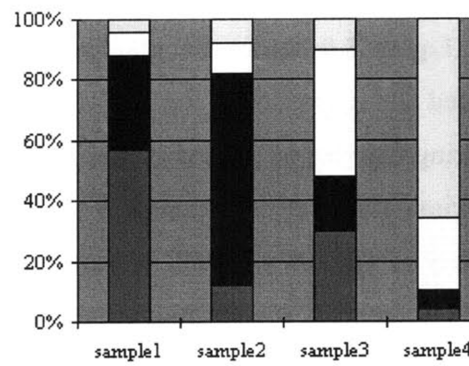
(c) Rate of Confusion at 10 Hz



(d) Rate of Confution at 32 Hz



(e) Rate of Confusion at 100 Hz



(f) Rate of Confusion at 250 Hz

■ answer sample1 ■ answer sample2 □ answer sample3 □ answer sample4

Figure 3.9 Confusion rate chart, varying the frequency from 1 to 250Hz

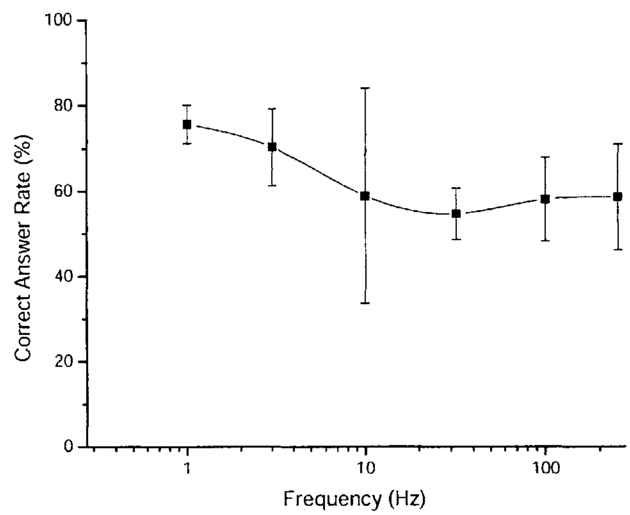


Figure 3.10 Mean correct answer rates with respect to frequency variation

Merkel cell-neurite complexes which are believed to produce the sensation of "pressure" in the frequency range of 0 to 3Hz are densely distributed on the fingertips [2, 7]. Therefore, a feasible interpretation is that the correct percentage is high in the low frequency ranges due to the activation of SAI afferents. Good performance around 32Hz might be attributed to activation of the Meissner corpuscles, which are densely distributed in the fingertips, respond to higher frequencies, but have coarser spatial resolution than Merkel cell-neurite complexes. Even though the density of Merkel receptors and Meissner's corpuscles are similar, the volume of a Merkel cell-neurite complex is much smaller than a Meissner corpuscle [2]. As a result, the spatial acuity of Merkel cell-neurite is better and hence the correct answer rate at low levels of frequency is higher than when at the frequency of 32Hz. Meanwhile, the difference in the number of vibrating pins makes the conspicuous energy difference between samples. As a result, the correct answer rate increases around 250Hz. However, the overall trend rate of the correct answers is decreasing because spatial acuity becomes worse as the stimulating frequency increases. For instance, at 250 Hz, subjects were liable to choose the second sample for the first sample and the first for the third one. They were also likely to confuse the third and fourth samples.

3.5.3 Identical power level

From section 3.5.2, we found that human spatial acuity changes with vibration frequency and generally it decreases as the frequency increases to high values. We guess that human may not discern whether the edges of each sample are sparse or dense at the ranges of high frequency where they showed low spatial acuities. However, it is possible that the different number of stimulating pins invoked detectable energy gaps between samples. In this test, the number of pins turned up remains constant in order to remove the effect of the difference in the vibration energy level.

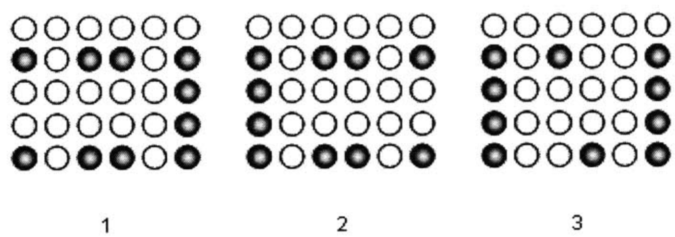
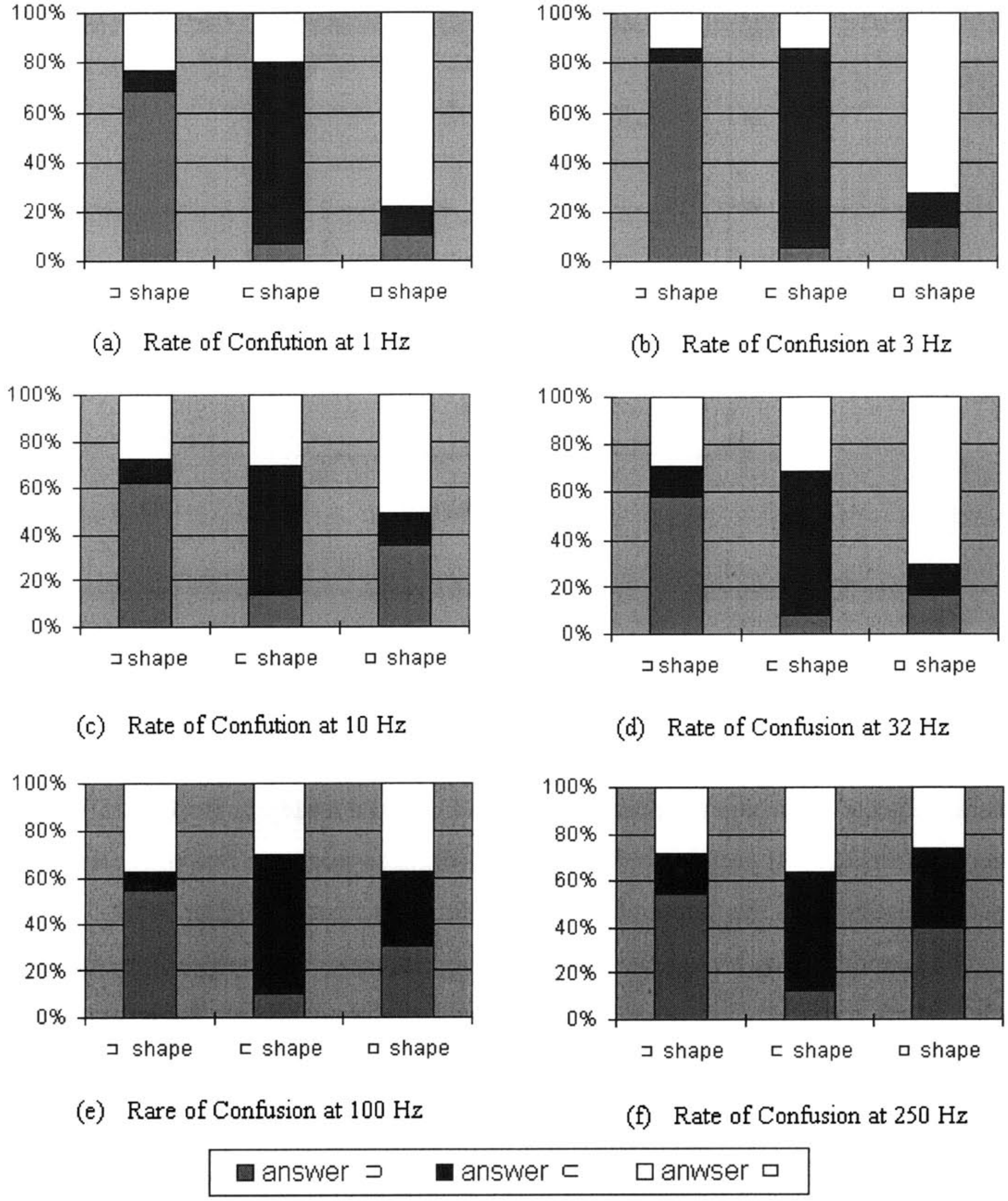


Figure 3.11 Samples for stimulation with identical power

Three patterns were displayed using 10 pins (Figure 3.11). The first and second samples have open ends at the left and right sides respectively and the third one is similar to a rectangle. Each texture pattern was displayed 5 times randomly at 6 frequencies, for a total of 90 trials.



(a) Rate of Confution at 1 Hz

(b) Rate of Confusion at 3 Hz

(c) Rate of Confution at 10 Hz

(d) Rate of Confusion at 32 Hz

(e) Rare of Confusion at 100 Hz

(f) Rate of Confusion at 250 Hz

Figure 3.12. The confusion rate chart, varying the frequency from 1 Hz to 250Hz

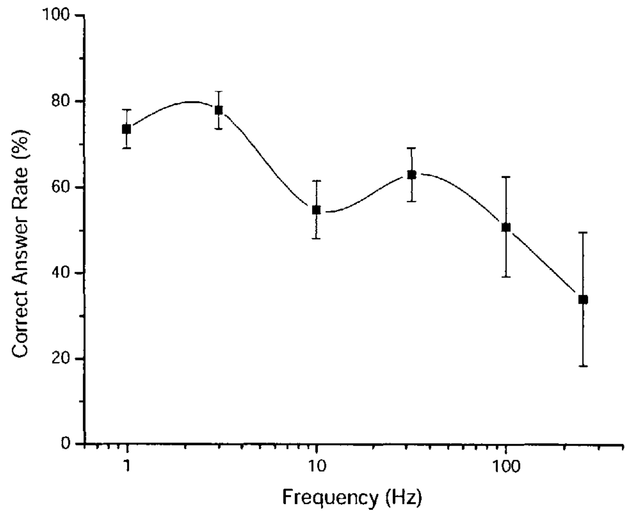


Figure 3.13 Mean correct answer rates with respect to frequency variation

Figure 3.12 shows the confusion trends for three equally energetic stimuli presented at 1-250 Hz. The overall trend in correct rate (Figure 3.13) is similar to that of the experiment in section 3.5.2 (Figure 3.10), with one notable exception. With energy held constant, subjects' discrimination performance did not hold steady in the 100-250 Hz range, but declined instead. It seems like the energy difference might be one of the cues for the subjects to discriminate the stimuli delivered to their finger pad in section 3.5.2.

The experimental results show that the subjects answered sample 3 for sample 1 or sample 2 as the frequency increased. It means that they did not discern the left or right edge of a rectangular which was presented with 2 pins or 4 pins. They rarely discriminated among samples at high frequency. The trend also shows a local maximum at 32 Hz though it is not significant statistically within 5% level ($p=0.067>0.05$). We might conclude that vibratory stimuli increase sensitivity rather than static touch and humans are more sensitive at the frequency ranges of 1-3Hz and 32Hz. These results could be explained based on the characteristics of tactile peripheral neural response.

There are four kinds of mechanoreceptors in the glabrous skin of the hand: Meissner's corpuscle, Merkel's disk, Pacinian corpuscle and Ruffini endings [2, 17]. Each afferent receptor has individual characteristics and functions such as responding frequency band, sensation quality, innervation density and spatiotemporal acuity. Many kinds of feeling of touch are perceived by the synchronous operation of these mechanoreceptors. The Pacinian corpuscles transmit the sensation of "vibration" in the frequency range of 40-500Hz and the best working range is 250-300Hz. However, the innervation density of them at the index fingertip is very low in comparison with that of Meissner or Merkel's receptors; they are much larger and located at greater depth from the skin surface.

Based on the neurophysiologic data for the glabrous skin, the correct answer rate at the frequency of 250Hz should be worse than that around the low frequency because of the lower spatial resolution of the Pacinian corpuscles. If so, the increase of right answer rate at the frequency of 250 Hz in experiment I must be caused by the difference in the energy level because the number of acting probes was not the same in each of the samples.

The reason the percentage of correct answers are higher at low frequencies, is perhaps due to the mediation of sensation through the Meissner's corpuscle and Merkel's disks that are distributed densely on the fingertip; these results are similar to those of experiment in the previous section. As the stimulating frequency increases, spatial acuity worsens, so the subjects become confused. To take advantage of this fact, we may be able to make people feel the sense of touching a rectangle with a sparser pin display at high frequencies. To sum up, the perception of spatially distributed stimuli would depend on the characteristics of each mechanoreceptor and the stimulating power level.

4 Perception of Compound waveform stimuli

This chapter presents a calibration test and two psychophysical experiments designed to investigate whether a compound tactile stimulus consisting of two discrete frequencies might be perceived as a single intermediate frequency. The "compound waveform" was a stimulus produced by 2 pairs of spatially-distributed contactors vibrating at two different frequencies, while the single frequency or "pure-tone" stimulus was produced by the same 4 contactors vibrating in phase, all with the same amplitude. Figure 4.5 shows the arrangement of the 4 contactors on the tactile display.

Experiment 1 (Section 4.3) involved a matching task that was designed to determine the pure tones which each subject perceived to be the best match for the given compound waveforms. Then, Experiment 2 (Section 4.4) tested the subjects' ability to discriminate between the compound stimuli and the corresponding individually best-matched pure-tones that were determined in the first experiment. Both experiments were performed by the same set of subjects, with each subject performing both experiments on the same day. The same subjects also performed a calibration test on a previous day so that the stimulus amplitude could be controlled more accurately.

4.1 Subjects

Ten right-handed subjects (8 men and 2 women) were used. Six of them were in their twenties and the others were in their thirties. Some of them had experienced the tactile display in the previous experiments (Chapter 3), but all of them were new to the experimental tasks in this chapter. Each performed both experiments (1 and 2) on the same day. The purpose of the study and the procedures were explained to the subjects before the start of the test. All were paid according to the participation time.

4.2 Calibration

The tactile display used as the apparatus in these experiments consisted of piezoelectric bimorphs as described in the previous chapters. In a previous test, the frequency response of the actuators was measured in the air under no load conditions [15]. Unfortunately, the normal displacement of the actuators varies depending on the reaction force of the skin. Further, the actual displacement of the pin pushing against the skin may be different from subject to subject because the subjects press on the surface of the display with different finger forces and the impedance of their skin might be different as well. The exact normal deflection of the skin is an important variable in the following experiments in order to control the power transmitted to the skin and the sensation level for each subject. Therefore, we need to measure the actual frequency response of the tactile display for each individual subject. This section describes the quantitative calibration of the display for each subject in the following experiments.

4.2.1 Procedure

The goal of this calibration was to figure out the relation between the input voltage and the actual displacement of the skin of each subject as the stimulating frequency increases. If the piezoelectric actuator mounted on the tactile display was very stiff and people couldn't deform it with their finger force, the measurement might be relatively easy. But the stripe type bimorph (40-1055, APC Int. Ltd.) has a characteristic that the total deflection decreases as the blocking force increases. Thus the measurement of the actual displacement of the skin depends on how much he or she presses against the contactor. In order to make subjects press the tactile display with the same force, a force-torque transducer (Nano 17, ATI) was mounted on a three-axis linear guide as shown in Figure 4.1. Although the force monitored may be different from the direct contact force at the interface, the fixture with the force sensor should improve the measurement system by reducing variability. Once the subjects put their finger on the tactile display, the z-axis (vertical) of the linear guide was moved down on their nail and adjusted so as to press down on the finger with 0.5N. The force level was monitored by the computer throughout the measurement. The test stimuli were sinusoidal waveforms sampled at 5 kHz. The stimulus involved only a single actuator on the display and lasted for duration of 1 second.

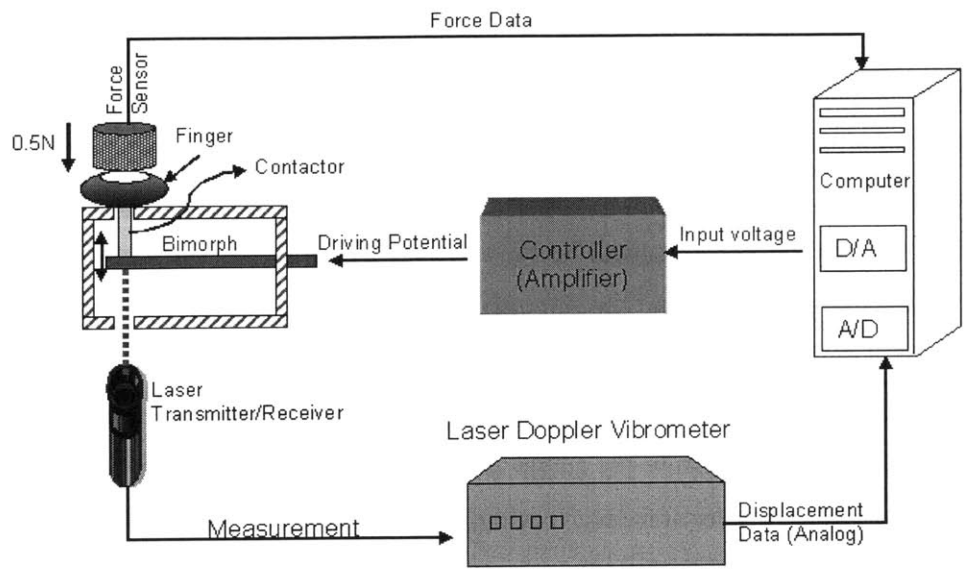


Figure 4.1 The measurement system for calibrating the actual displacement of human skin. Note that the force sensor and the Doppler vibrometer were only used in the calibration test, not in the following actual experiments.

The actual displacement was measured in the calibration test by a non-contact method using a laser Doppler vibrometer (OFV511, Polytec) which has submicron resolution. The measured signal was collected by an A/D card (NI-6014, National Instruments) with a sampling rate of 5 kHz which is fast enough not to cause aliasing. For noise reduction, the signal was filtered by a band pass digital filter centered on the stimulating frequency.

The measurement was done on each of the ten subjects at three test frequencies; 30, 135, and 240Hz, which correspond to the slow, medium and fast stimuli used in Experiment 1. Because the compound waveform consists of two components (30 and 240Hz), it is sufficient to measure the frequency response at these frequencies. Moreover, the bimorph has the linear characteristic up to the resonance frequency, so I can use this calibration to generate signals in the other intermediate range. At each test frequency, I measured the actual displacement of the contactor as I increased the input voltage from 1V to 6V. Note that the input voltage means the peak-to-peak electric potential.

4.2.2 Results

Figure 4.2 shows the response of the actuator to the input voltage at the three test frequencies under no load conditions; i.e., in air without any contact with human skin. The average results for the ten subjects under contact conditions are presented in Figure 4.3. When the input voltage is below 1 volt, the displacement does not seem to be linear and it does not converge to the origin, either. This bad characteristic near zero is caused by the amplifying circuit which does not work lineally around the zero input voltage. But, the linear characteristic of the bimorph is valid for the ranges used in the experiments.

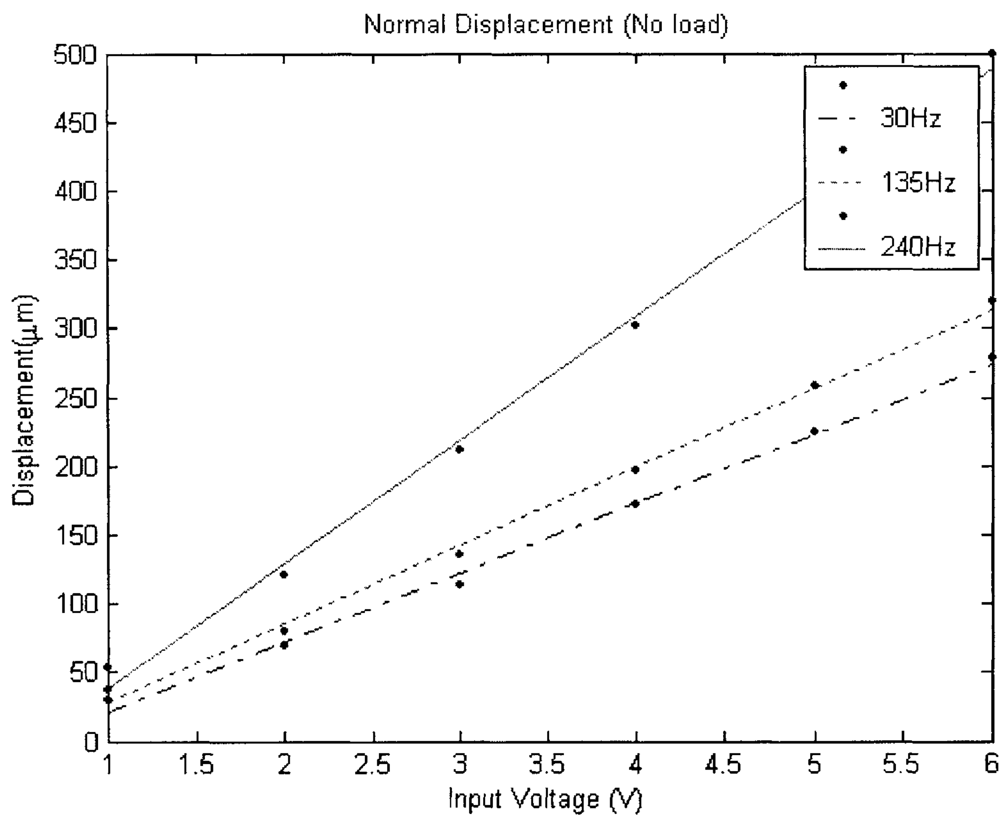


Figure 4.2 The displacement of the contactor without load

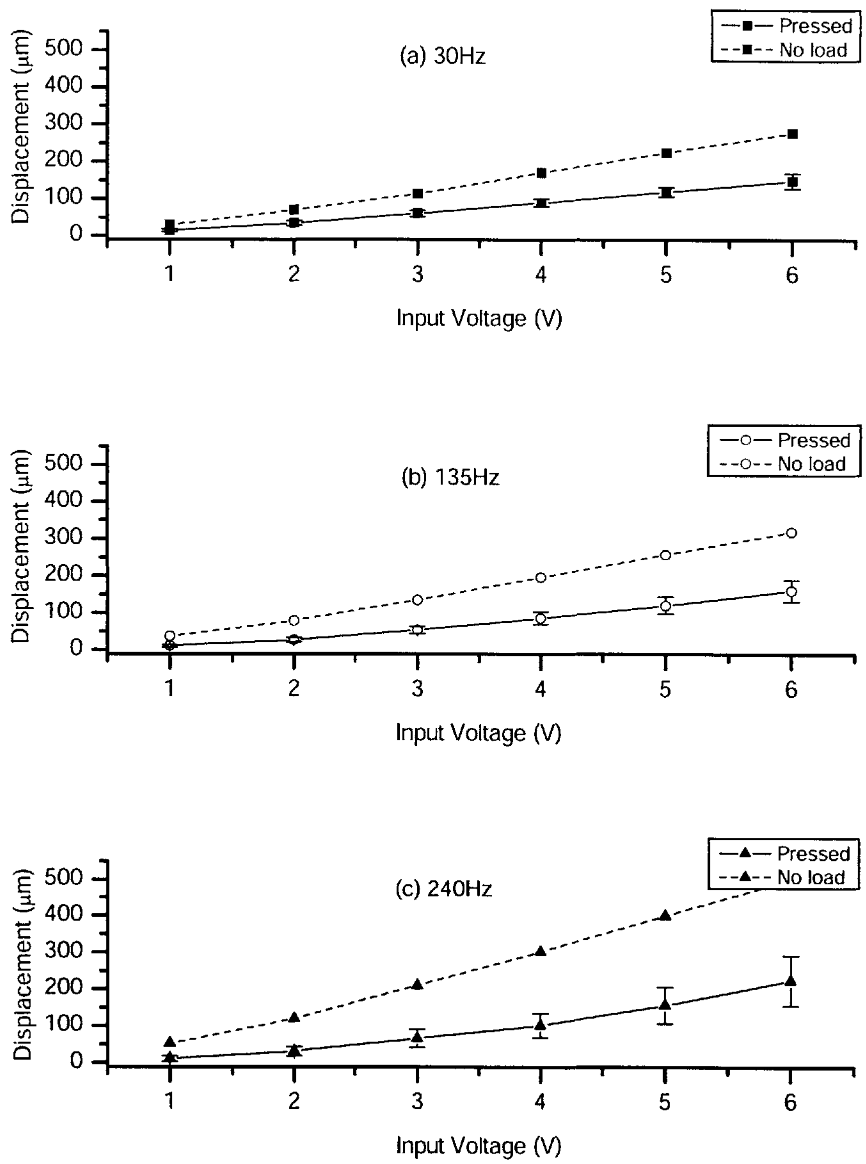


Figure 4.3 The actual skin travel length when pressed as the input voltage increases. The data of each subject are in the Appendix B

The actual skin displacement was different from subject to subject as shown by the individual results presented in Appendix B. In most cases, however, except for the response of Subject 4, the actual displacement decreases about 50% compared to the response in air. The response of Subject 4 was 65% of the no load response. The slope of the best-fit line is steeper at 240Hz by 14.14μm/V than at 30Hz and 135Hz. This is caused by the frequency response of the actuator near the resonance frequency and the impedance of the skin. The frequency responses at 30Hz and 135Hz are similar to each other because these frequencies are much lower than the bandwidth (325Hz) and hence the frequency response is kept constant.

Based on the individual results, I generated the corresponding input signals for the following psychophysical experiments so that each subject could be stimulated with the same displacement calibrated by his or her own frequency response.

4.3 Experiment 1: Frequency Matching-compound to pure

In this section, I describe a psychophysical experiment in order to investigate the effect of the power ratio of the primary component frequencies on the perceived frequency using the tactile display to deliver a spatially distributed stimulus. The primary vibrotactile components were determined on the basis of the psychophysical literature on the channel mechanism for tactile sensation [3].

4.3.1 Stimulus

The perception of vibration is mediated largely by two psychophysical channels, the Pacinian (P) and the non-Pacinian I (NPI), as demonstrated in numerous studies [3, 8, 9, 11, 18-21]. In this section, these two primary components are spatially distributed in order to make an analogy of RGB in computer graphics as shown in Figure 4.4. The low and high frequency components used in the present experiments were 30 and 240Hz. These specific frequencies were selected to approximately match the most sensitive frequencies of the Meissner corpuscle (NPI or RA) and the Pacinian corpuscle (P), respectively [7]. All stimuli were sinusoidal without any phase difference in the same components.

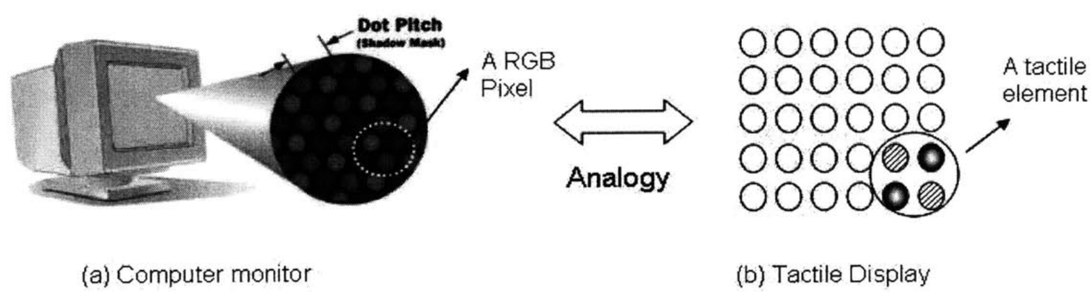


Figure 4.4 Analogy between a pixel and a tactile element

I attempted to vary the effective frequency of the compound waveform by changing the power ratio of the two primary component frequencies. The power was set so that the sensation level would be much higher than the sensation threshold [22]. The mechanical power transmitted to the skin is calculated as follows, assuming constant impedance (k) of the skin, which is reasonable because the effect of change in the skin impedance on the normal displacement is much smaller than that of change in input voltage.

$$Mechanical\ Power_{peak-to-peak} = kf_i A_i^2 \quad (4.1)$$

Five compound waveforms with the different power ratios (but the same total power) were used. The power ratio of each stimulus is summarized in Table 4-1 and Figure 4.5 shows the arrangement of the stimulator pins. The initial value of the amplitude of the pure-tone stimulus was decided so that the summation of the power of the 4 active pins was constant for all stimuli.

$$P_{total} = 2A_{30Hz}^2 f_{30Hz} + 2A_{240Hz}^2 f_{240Hz} = 4A^2_{pure-tone} \times f_{pure-tone} \quad (4.2)$$

The onset time for all stimuli was the same and the duration was 1 second.

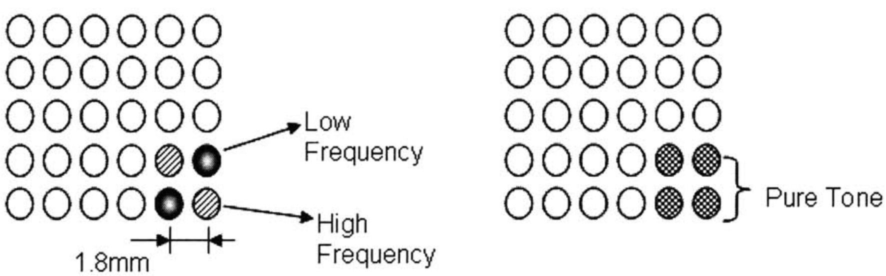


Figure 4.5 Contactor configurations of a compound waveform (left) and a pure-tone (right)

4.3.2 Procedure

Before the experiment began, the subjects read the provided instruction (Appendix A) of the experiment and asked any questions about the procedure (except the precise nature of the "compound vibrotactile stimulus"). Then I had him or her read and sign the informed consent form approved by the MIT Committee On the Use of Humans as Experimental Subjects (COUHES, protocol number 1980).

The subjects were seated in front of the computer monitor with their left index finger on the tactile display after they put on the earmuffs in order to avoid the audible noise. They used their right hand for controlling the computer mouse. The subjects were asked to adjust a pure-tone to a given compound stimulus changing the frequency and the amplitude of the pure-tone. A compound stimulus out of 5 compound waveforms (Table 4-1) was presented randomly. Each stimulus was presented three times for a total of 15 trials.

Compound waveform	Displacement (peak-to-peak) (μm)	Sensation Level (dB)	Power Ratio (P_{low} : P_{high})
CW1	A_{30Hz}=196	41	3:1
	A_{240Hz}=40	51	
CW2	A_{30Hz}=184.8	40	2:1
	A_{240Hz}=46.2	53	
CW3	A_{30Hz}=160	39	1:1
	A_{240Hz}=56.6	55	
CW4	A_{30Hz}=131	38	1:2
	A_{240Hz}=65.3	56	
CW5	A_{30Hz}=113.1	37	1:3
	A_{240Hz}=69.3	57	

Table 4-1 Specification of the compound stimuli

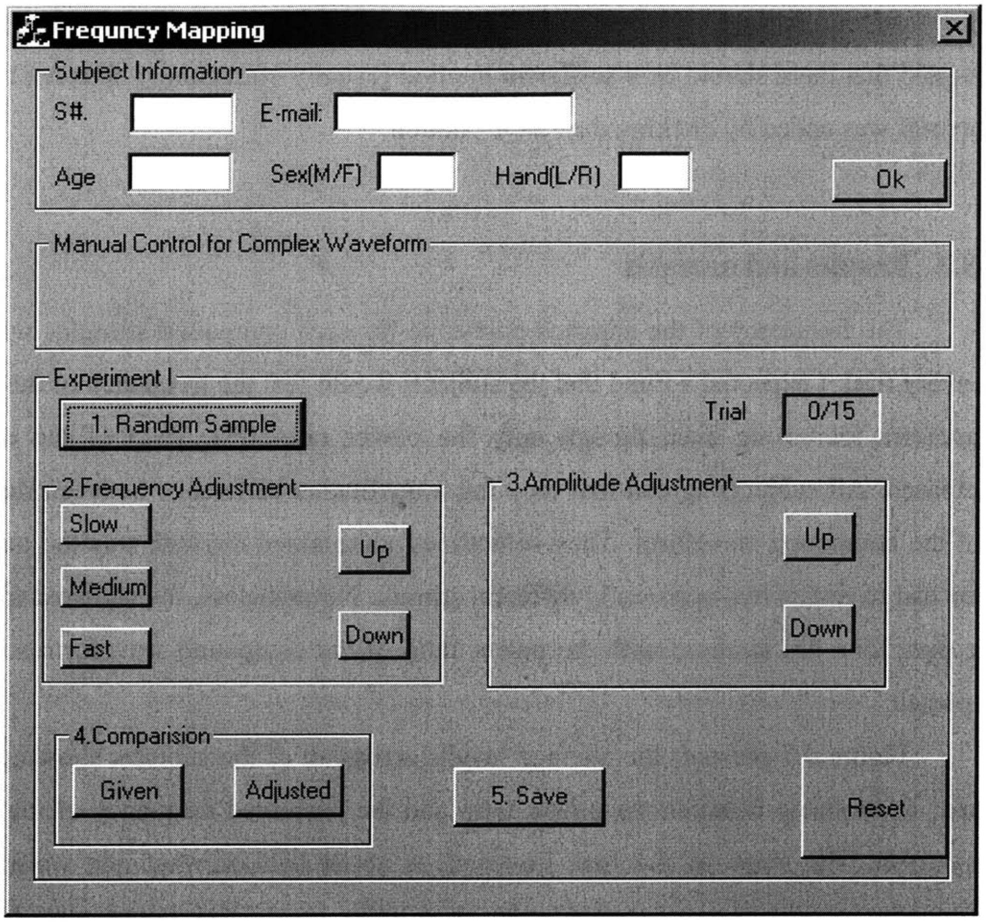


Figure 4.6 GUI for Experiment 1: Compound to Pure Matching

Figure 4.6 shows the graphic user interface for this experiment which was operated by the subject while performing the test. In the experiment, the subject got a sample by clicking the button "Random sample" in the GUI. They then roughly estimated the range of frequency of the given compound stimulus and started the pure tone by selecting the desired initial frequency: "Slow" (30Hz), "Medium" (135Hz) or "Fast" (240Hz). Before the real test, they got a sense of these three stimuli through a practice session. "Up" and "Down" buttons were used for further adjustment to try to match the pure tone to the compound waveform. The incremental step was set to ±4Hz. After the subject felt that the adjusted frequency was as close a match as possible to the given stimulus, they moved to the next section for the amplitude adjustment. The increment of the amplitude was set to

±5μm. The subject was allowed to replay the stimulus as many times as he or she wanted using the "Comparison" section. In order to minimize the affect of adaptation, the subject was told that there should be a sufficient interval (usually 10 seconds) between two stimuli. The trial was ended by clicking the "Save" button.

4.3.3 Results and analysis

The frequency of the adjusted pure-tone for each compound stimulus was recorded in every trial. I expected a trend that the subjects would feel the frequency of the compound waveform increasing even though only the power ratio (P_{high}/P_{low}) of the components increased. All subjects agreed that they felt a qualitative difference between the pure-tone and the compound waveform. They sometimes complained the task was too hard because they had to match two apparently different stimuli. Nevertheless, the adjusted frequency of the pure tone did increase with the power ratio of the compound waveform somewhat as expected.

Figure 4.7 presents the average results across all of the subjects showing a roughly linear relationship between the power ratio and the perceived frequency of the compound waveform. The slope of the line, however, is about half of what one would expect if frequency judgments were based only on a ratio code. There was also considerable variation between subjects.

Figure 4.8 shows the individual results for each of the ten subjects. In each graph, a line was fitted to the data points based on the least square method. The correlation coefficients (R) show that there is a significant positive correlation between frequency and power ratio. However, the range of their responses was too large to find out general relation for all subjects as shown Figure 4.8.

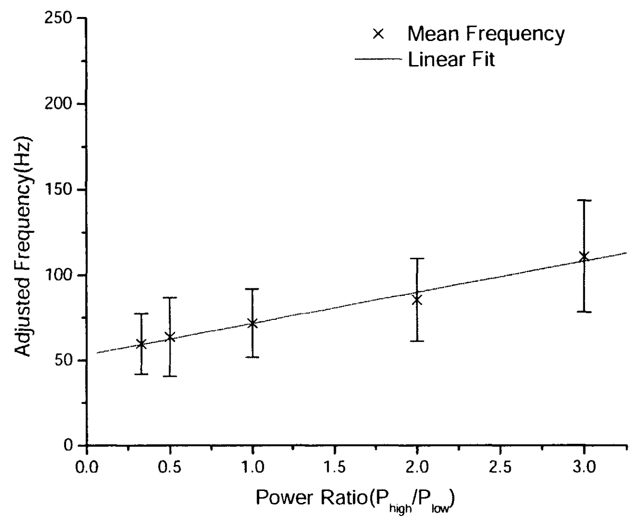


Figure 4.7 Mean adjusted frequency averaged over all of the subjects

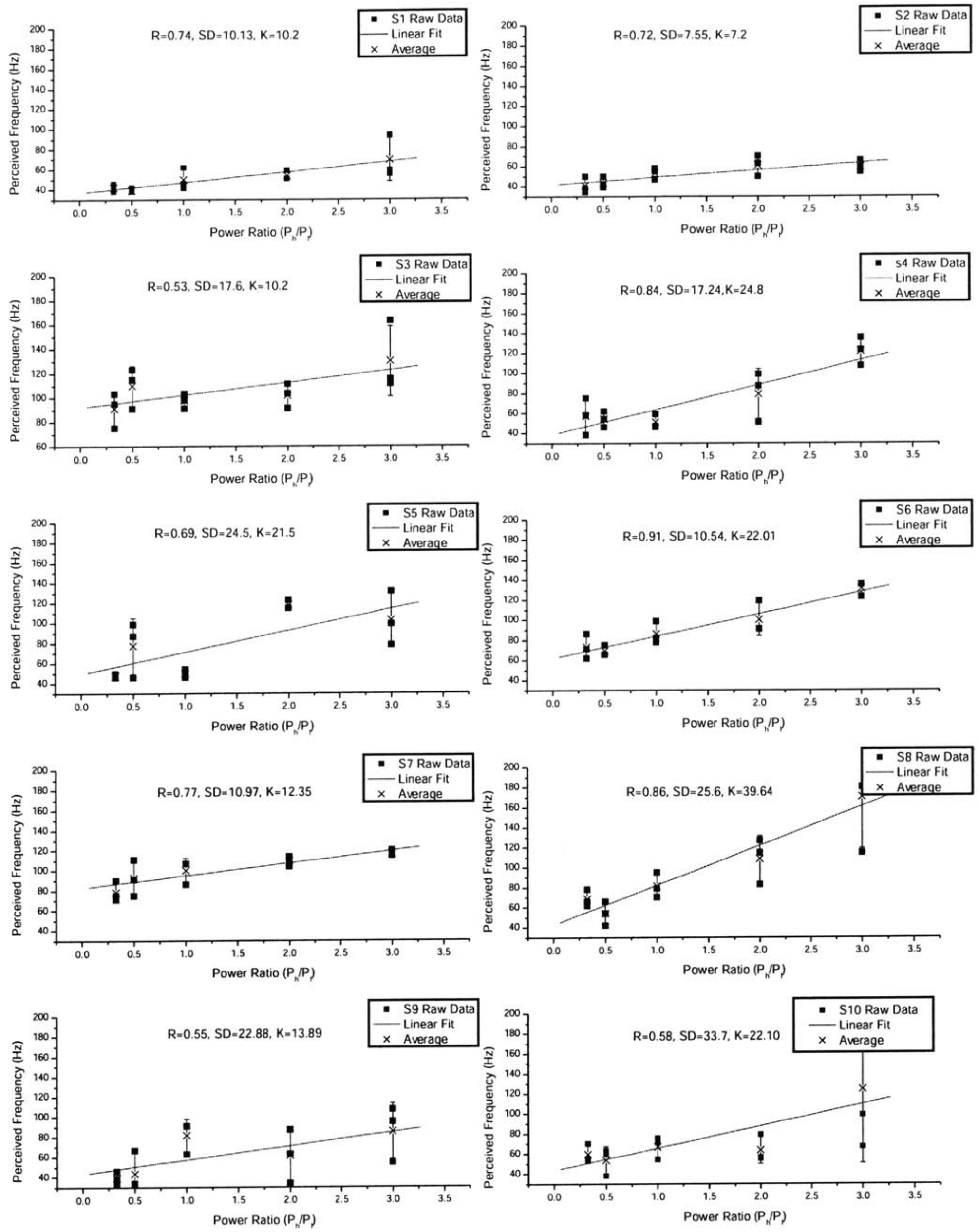


Figure 4.8 Result of Experiment 1: Compound to Pure-tone Matching (R: Correlation Coefficient, SD: Standard deviation of Linear fit, K: slope).

The slope of the fitted line in Figure 4.8 presents the sensitivity of the subject to the high frequency component. In other words, we can estimate the extent from the slope that the subject is confounding change in the power ratio with change in frequency. However, there is still intersubject variability in the fitted line slopes of the individual results. For example, the result of Subject 2 and 3 shows that they didn't feel the much difference between the five compound waveforms which have the same frequency component but have different power ratios, while Subject 4 and 6 seems to have felt significant increase in frequency as the power of high frequency increased.

For statistical validity, a two-way ANOVA (analysis of variance) test was conducted on the results [23]. The two factors were the participated subjects (factor A) and the power ratio (factor B). Each treatment combination is replicated 3 times, which enables the interaction effect to be estimated. In general, the interaction significance test should be done first because it is not appropriate to test the factor A and B effects separately if the interaction is significant on a statistical basis [24]. Analysis was done using the statistics toolbox in MATLAB®.

Response model: Statistical model for the adjusted frequency (X_{ijk})

$$X_{ijk} = \mu_{ij} + \varepsilon_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \tag{4.3}$$

where i=1,2...5, j=1,2,....,10 and k=1,2,3.

The μ term refers to the grand mean which is assumed constant. The α_i term is the effect of the ith power ratio level and β_j is the effect of the different subjects. The interaction term, $\alpha\beta_{ij}$, measures the combined effect of the power ratio and subject, which means the two factors influence the response in combination and not independently.

Hypotheses:

H_{0AB}: no interaction effect occurring.

H_{0A}= all samples from factor A are drawn from the same population, i.e. there is no significant difference between subjects.

H_{0B}= all samples from factor B are drawn from the same population, i.e. the subjects didn't feel the 5 samples significantly different.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	52474	9	5830.4	16.1	0
Rows	51895.3	4	12973.8	35.83	0
Interaction	26519.8	36	736.7	2.03	0.003
Error	36208	100	362.1		
Total	167097.1	149			

Figure 4.9 ANOVA Table for Experiment 1

In Figure 4.9, the interaction *p* value, 0.003, is low enough to reject the null hypothesis H_{0AB}, which indicates the power ratio level and the difference in subjects interact in their effect on the adjusted frequency with significance level of 5%. Since the interaction is significant, the *p* value for the separate effect of individual factors in the Figure 4.9 cannot be validated by this analysis because it would not be correct [24]. The interaction means that each subject might feel the difference of the 5 power ratio levels but the extent of that difference depended on the subject.

Next, in order to analyze the effect of the power ratio for each subject, one factor ANOVA test was conducted for the individual results. The null hypothesis for each test was the same as H_{0B} in the two factor analysis. The *p* value for rejecting the hypothesis is summarized in Table 4-2. Seven results of the ten subjects gave such a small p value that rejects the null hypothesis, which means that those subjects were significantly affected by the power ratio when determining the best-matched pure-tone.

Subject	p	H_{0B} Reject/Accept	Subject	p	H_{0B} Reject/Accept
S1	0.0521	Accept	S6	0.0003	Reject
S2	0.0221	Reject	S7	0.0136	Reject
S3	0.1311	Accept	S8	0.0024	Reject
S4	0.0014	Reject	S9	0.0693	Reject
S5	0.0019	Reject	S10	0.1582	Accept

Table 4-2 One way ANOVA test for individual subjects. 7 of the subjects reject the null hypothesis with 5 % significance level, so we could statistically say that the power ratio affected the perceived frequency for those subjects.

4.4 Experiment 2: Discrimination of compound waveform

In order to investigate the sensitivity to the compound waveform described in the previous section, a discrimination test was conducted using the same subjects after they finished Experiment 1, following a short break. In Experiment 2, the subjects used a *same-different* paradigm [25, 26] to discriminate between a compound waveform and the average pure-tone that they had adjusted to the given compound waveform in Experiment 1.

4.4.1 Procedure

The subject was seated in front of the computer monitor with his or her left index finger on the tactile display. All other test conditions were also the same as Experiment 1. For each compound waveform, the subject did the discrimination task 20 times. On each trial, a pair of stimuli were presented by the tactile display for 1 second each, with a 1 second interval in between, and the subject was to determine whether the stimuli were the same or different. Feedback was given as to whether the response was "correct" or "wrong" at the end of each trial. The possible stimulus pairs were $<S_{cw}, S_{cw}>$, $< S_{pure}, S_{pure} >$, $< S_{cw}, S_{pure}>$, and $< S_{pure}, S_{cw}>$. The S_{cw} stimulus is one of the 5 compound waveforms described in Table 4-1 while S_{pure} is the pure-tone which has the average frequency that the subject had adjusted to the S_{cw} in Experiment 1. To eliminate time error caused by the sequence of the stimulus, the 4 pairs were presented 5 times each in random order. Thus, 20 trials were done for each S_{cw} and each subject ran a total of 100 trials. The 5 trial runs were done in the order that the compound waveforms are listed in Table 4-1.

Figure 4.10 shows the GUI for Experiment 2. Each trial began when the subject clicked the "Sample" button, causing a pair of stimuli to be presented (clicking the button again at this point did not cause the same stimuli to be repeated). The subject then determined whether the stimuli was the same or different and clicked the appropriate button. After the response was given, the subject started the next trial by clicking the "Sample" button to get the next stimulus pair.

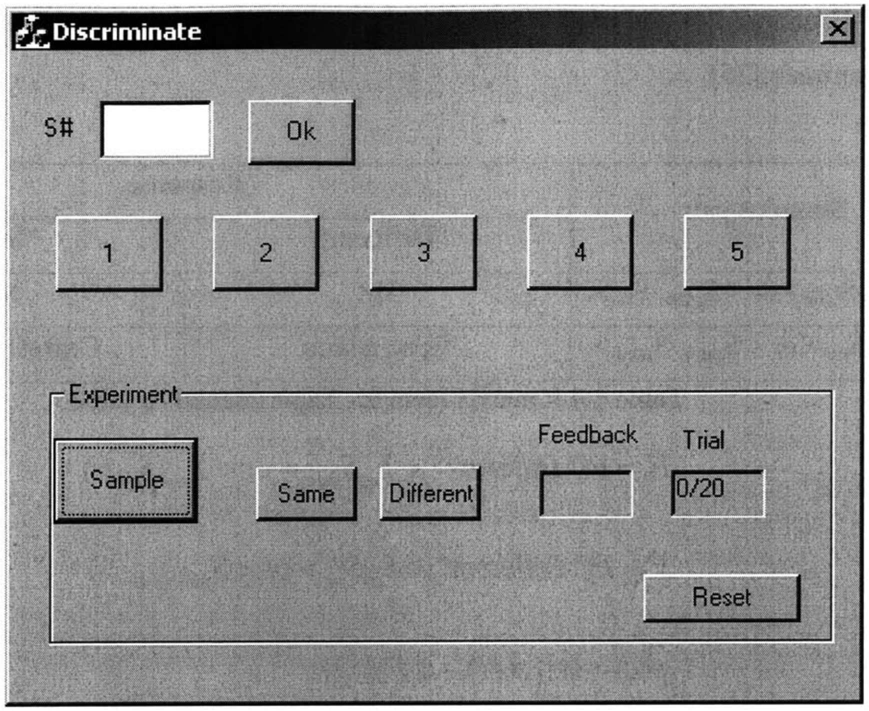


Figure 4.10 GUI for Experiment 2: Discrimination

4.4.2 Results and analysis

In order to measure the sensitivity to the different stimuli, I used Signal Detection Theory (SDT) [25-27]. The experimental results of each subject were rearranged in the form of Table 4-3 which has four cases. The "Hit" term stands for the number of "Different" responses when the stimuli in the pair were different, while "False Alarm" means the number of "Different" responses when the stimuli were the same. Using the hit rate and false alarm rate in SDT, it is possible to calculate a measure of sensitivity, d', which is independent of the subject's response bias.

Figure 4.11 shows curves of constant d' where different points on each curve correspond to observers with the same sensitivity but with different levels of bias. A diagonal line running from the upper left corner (0,1) to the center (0.5,0.5) corresponds to an unbiased observer. While, for example, observers to the upper right of this line would be biased toward responding "Different".

Equation(4.4) was used to calculate d' from the observed hit and false alarm rates in the experiment[25].

Stimulus pair	Response	
	"Different"	"Same"
$< S_{cw}, S_{pure}>$ or $< S_{pure}, S_{cw}>$	Hit	Miss
$<S_{cw}, S_{cw}>$ or $< S_{pure}, S_{pure} >$	False Alarm	Correct Rejection

Table 4-3 A matrix form for Experimental Result 2

$$H = P(\text{"Different"} \mid < S_{cw}S_{pure} > or < S_{pure}S_{cw} >)$$

$$F = P(\text{"Different"} \mid < S_{cw}S_{cw} > or < S_{pure}S_{pure} >)$$

$$p(c) = \Phi\{[z(H) - z(F)]/2\} \tag{4.4}$$

$$d' = 2z[0.5\{1+[2p(c)-1]^{1/2}\}]$$

$$\Phi(z) = \frac{1}{\sqrt{2\pi}}\int_0^z e^{-x^2/2}dx = \frac{1}{2}erf(\frac{z}{\sqrt{2}})$$

where H is the hit rate and F is the false alarm rate. P stands for probability calculation. $\Phi(z)$ is the normal distribution function. z(H) and z(F) correspond to the values of z-score of hit rate (H) and false alarm rate (F), respectively.

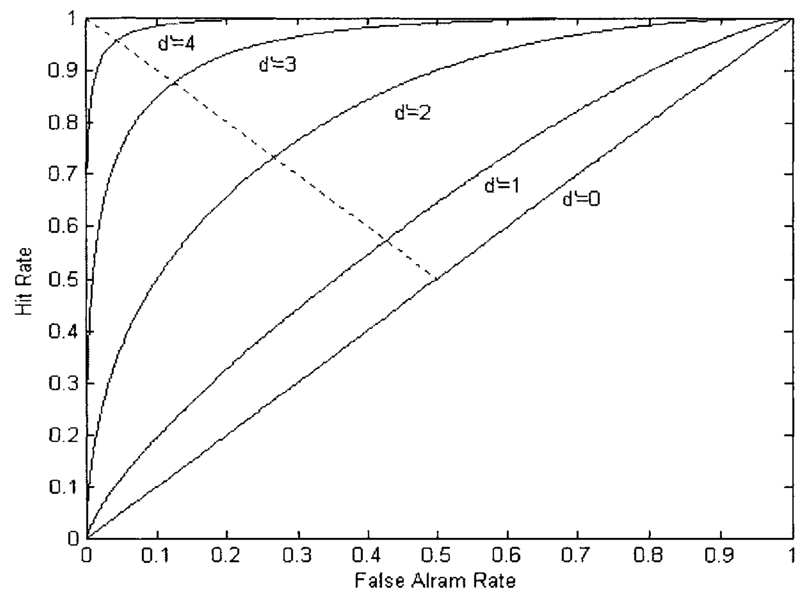


Figure 4.11 ROC[1]s for same-different method, all points in a curve have the same sensitivity d' [25]

[1] ROCs: Receiver operating characteristics

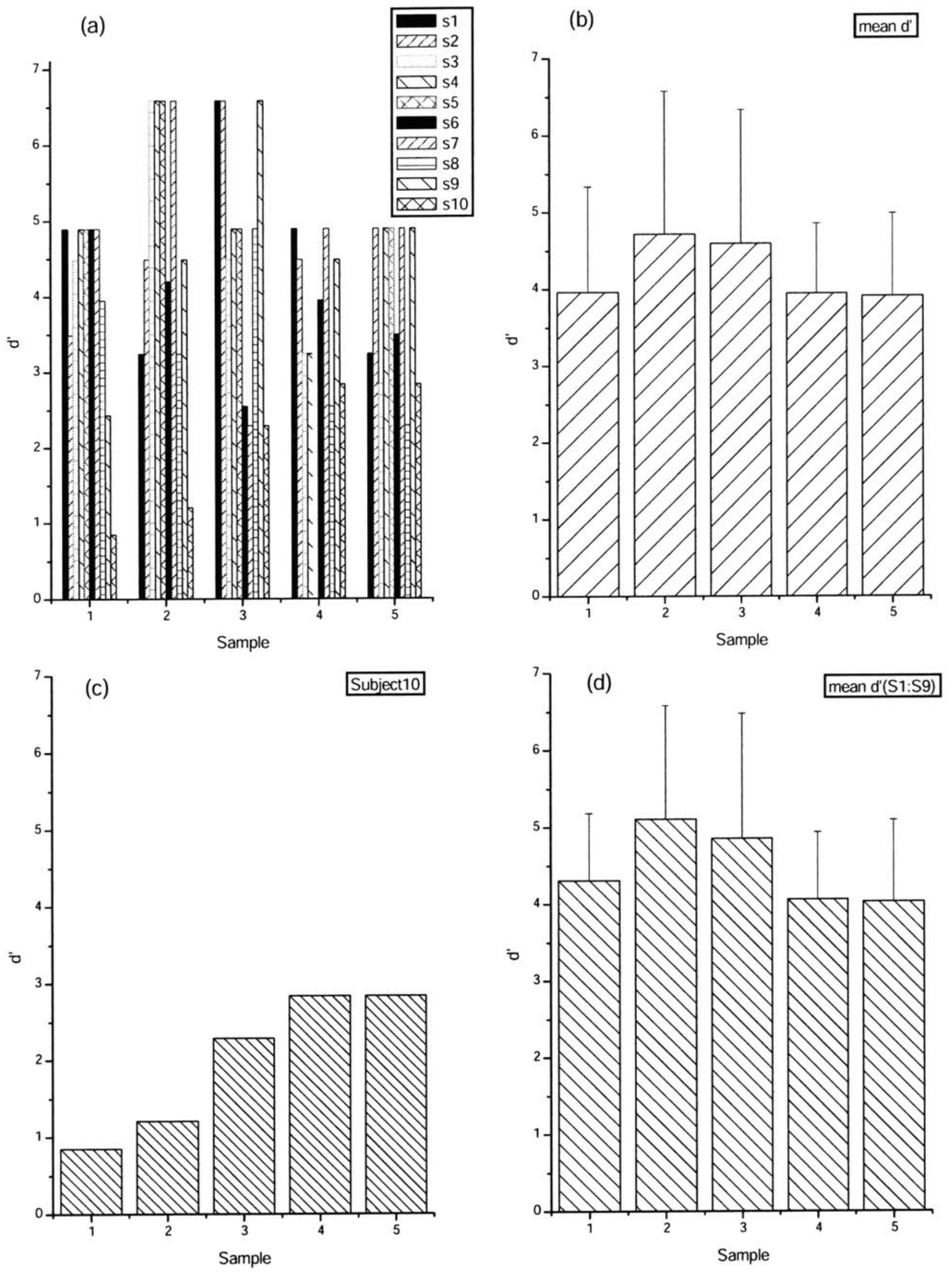


Figure 4.12 Result of Experiment 2, (a) individual results, (b) mean d' of 10 subjects, (c) d' of Subject 10, (d) mean d' of 9subjects

Figure 4.12 presents the results of Experiment 2 in terms of sensitivity, d'. The mean d' for each compound waveform is about 4.0. Assuming that the subjects were unbiased this corresponds to a correct response rate of about 95% (see Table 4-3 and Figure 4.11). In other words, the subjects can tell the difference very easily between a compound waveform and a pure-tone. In Experiment 1 the subjects were forced to match a pure-tone to the given compound waveform with different power ratios, which might be a hard job because the subjects seldom confound them in this discrimination task. Figure 4.12(c) represents that only Subject 10 showed a different trend from the others with 5% significance level, which was tested by two-way ANOVA and pair-wise comparison using MATLAB® . She seems to confuse the pure-tone which she had adjusted to the given compound waveform in the low frequency range. The response of rest 9 subject (S1~S9) are not different with 5% significance level.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	12.8745	8	1.60931	1.1	0.3875
Rows	8.4284	4	2.1071	1.44	0.2426
Error	46.7237	32	1.46012		
Total	68.0267	44			

Figure 4.13 ANOVA table of S1~S9, p is much larger than 0.05, so the null hypotheses can't be rejected, i.e. d' doesn't depend on subjects or the samples. Subject 1~9 always easily discriminate between a compound waveform and a pure-tone.

When the ANOVA test was conducted to all subjects including Subject 10, the null hypothesis was rejected, which means the d' depends on the subjects. However, the probability level of the other 9 subject was high (0.3875>>0.05) enough to exclude her data for this analysis.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	40.3763	9	4.48625	3.09	0.0075
Rows	6.2884	4	1.5721	1.08	0.3797
Error	52.288	36	1.45244		
Total	98.9526	49			

Figure 4.14 ANOVA table of all subjects including Subject 10, null hypothesis for column (subject) is rejected.

In brief, the results of Experiment 2 apparently show that the compound waveform is qualitatively different from the pure-tone and the subjects can discriminate without much difficulty.

5 Analysis and Discussion

The experimental results of the previous chapter show a general trend in tactile perception of spatially distributed stimuli, although there is much irregularity between the subjects. To help analyze the results, follow-up experiments were performed as described in this chapter. In terms of experiment design, Experiment 3 is a control group in which the subjects are asked to estimate the frequency of a given pure-tone and match it to a corresponding pure-tone, but in contrast to Experiment 1 in which they adjusted a pure tone to a given compound waveform. Experiment 4 is a measurement of differential frequency thresholds as a function of frequency. If the differential thresholds grow high enough over a certain range, it might explain why people are not able to tell the difference between a compound waveform and a pure-tone over that range. In addition, variability the difference thresholds between subjects might explain some of the variability of the prior experimental results. In addition, a model to explain the experimental result is presented in the later part of this chapter.

5.1 Experiment 3: Frequency Matching-pure to pure

Basically, Experiment 3 is a follow-up test for the subjects' initial ability in matching task itself. In Experiment 1, some of subjects showed high correlation coefficient ($R>0.8$) between the power ratio and the perceived frequency while others didn't respond much differently to the change of stimulus. The difference of these two groups could be found in the correlation coefficient and the slope of the fitted line in Figure 4.8. Based on these two standards, I picked six subjects and divided them into two groups, in order to investigate whether they had any difference in the ability of performing the matching task. Since some of the ten subjects in Experiment 1 were not available for this follow-up test, I used 6 subjects in this verification experiment. The 6 subjects for this experiment are summarized in Table 5-1. The three subjects who gave highly correlated results are in Group I while the other three subjects in Group II have shown a low slope or a low correlation coefficient.

Group	Subject No.	Correlation Coefficient, R	Slope	Standard Deviation
I	S4	0.84	24.8	17.24
	S6	0.91	22.01	10.54
	S8	0.86	39.64	25.6
II	S2	0.72	7.2	7.55
	S3	0.53	10.2	17.6
	S9	0.55	13.89	22.88

Table 5-1 Subjects for Experiment 3. Even though S2 shows high correlation coefficient, the slope is very low, i.e. he didn't feel much difference between five compound waveforms, so he's in Group II

5.1.1 Procedure

Basically, the procedure of this experiment is equivalent to the Experiment 1 except for the stimulus provided because it is a control experiment of Experiment 1 which holds constant all variables but the one under observation. I prepared five pure-tones to be adjusted instead of the compound waveforms. Five pure-tones were set to 30, 60,120,180, and 240 Hz. The amplitude of these 5 stimuli was determined to give the same level of total power as Experiment 1. I also used the same GUI for Experiment 1 (see Figure 4.6) and the subjects were not aware of any difference in the experimental procedure.

5.1.2 Results and analysis

All subjects spent less time for this experiment while they usually hesitated to proceed to the next step in Experiment 1. It is reasonable that this task was clearer and easier to find a match than the "compound to pure" matching task. Figure 5.2 shows the result of each subject. All subjects did a good job of adjusting the stimulus to the given pure-tone. There seems to be no difference in their ability to find out the closest match. In addition, it could be shown statistically using the two-way ANOVA. One factor is the subject, the other one is the frequency of the given stimulus. Firstly, the interaction *p* value can't reject the null hypothesis, i.e. there is no interaction effect on the result with significance level 5%. In this case, we can test the separate main effects unlike the results of the Experiment 1 whose interaction effect was significant. The columns (for subjects) *p* value is almost chance-level (0.5) and easily accept the null hypothesis, i.e. there is no difference between the subjects. However, the rows *p* value is near zero, which means the subjects easily noticed the difference in vibratory frequencies of the given samples.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	1512.5	6	252.1	0.92	0.4841
Rows	613905	4	153476.2	561.81	0
Interaction	7725.9	24	321.9	1.18	0.2915
Error	19122.7	70	273.2		
Total	642266.1	104			

Figure 5.1 ANOVA table from the result of Experiment 3.

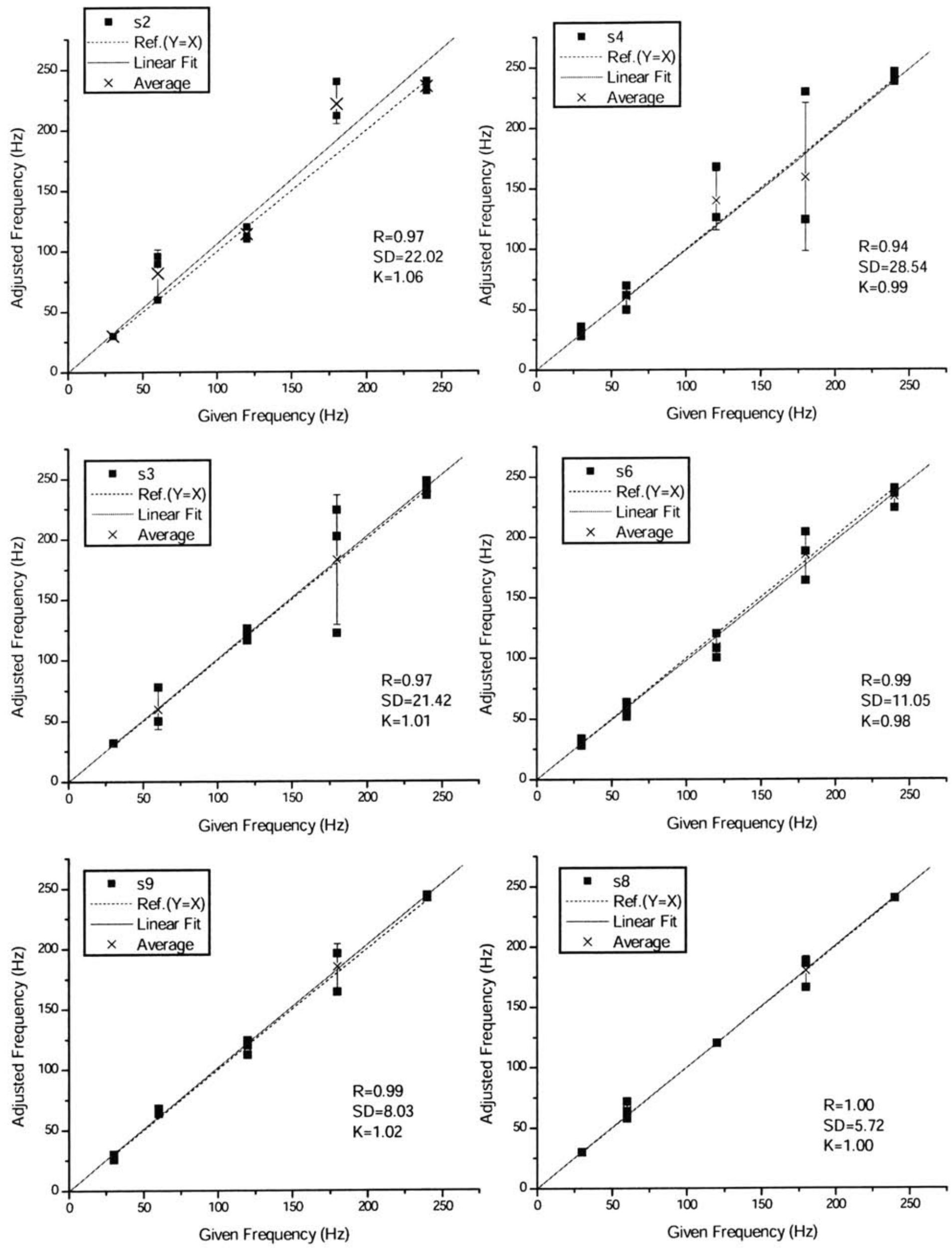


Figure 5.2 Results of Experiment 3, Pure-to-Pure matching

5.2 Experiment 4: Differential Threshold

Measurements of differential threshold for frequency might be another follow-up test to investigate the difference between two groups described in Table 5-1. If the subjects in one group has smaller difference threshold (DL for German *Differenz Limen*,[28]), it might explain the trend different from each other in the Experiment 1. For example, suppose the subjects in Group I, who sensitively responded to the change in the power ratio of the two components, have the lower DL than those in Group II. Then their trend might be interpreted in a way that they were more sensitive to the vibratory stimulus than those in Group II and noticed well the change in the power ratio or amplitude of the stimulus. However, they confused the change in the power ratio or amplitude with the frequency. In contrast, if the subjects in Group II have the lower DL and can tell the difference in frequency independently (i.e. regardless of the changes in the amplitude or power ratio), they might have had difficulty to feel the difference between the five compound waveforms which commonly have two constant vibratory frequencies (30 and 240Hz) with different power ratios or amplitudes. So their results of Experiment 1 might were not methodical.

Whichever explanation for the result of the Experiment 1 is more plausible, DL experiment itself is worthy because the original idea about "haptic color" would work if the DL increases infinitely in the range of high frequency as people can't see the individual RGB pixels in the monitor.

5.2.1 Procedure

Using the method of limits, a way of measuring the difference limens, I decided the DLs of each subject at 5 standard frequencies of the equal intensity of 40 dB SL[1] above the absolute threshold of the 250Hz standard based on the Verrillo's data.[7, 22, 28, 29]. There have been a lot of studies on measuring the DLs, but the results depended on the experimental conditions such as the contactor area, standard frequencies, sensation level

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[1] SL: Sensation Level

and even participants [18, 22, 30, 31]. Therefore, I needed DL measurements corresponding to my experimental apparatus and subjects.

In order to keep constant the other experimental conditions, the stimulus was given by the same 4 contactors of the tactile display that used in the previous experiments (Figure 4.5). The subject was seated in the same position with his left index finger on the tactile display and put earmuffs on as before. The experiment began with setting the standard frequency, and the subject got two stimuli lasting 1 second with 1 second interval. In terms of the sequence, the standard stimulus alternated with the comparison stimulus. The subjects responded to the stimuli by pressing either button of "equal" or "different". An ascending session and descending session alternated with each other. Each session began with the "equal" response, and increased the gap between the standard and the comparison stimulus by ±4Hz. When the subjects reported "different" three times in succession, they had to move to the other session. After each session was repeated 5 times, they rested for 10 minutes. The subjects run the same procedures for the other 4 standard stimuli.

5.2.2 Results and analysis

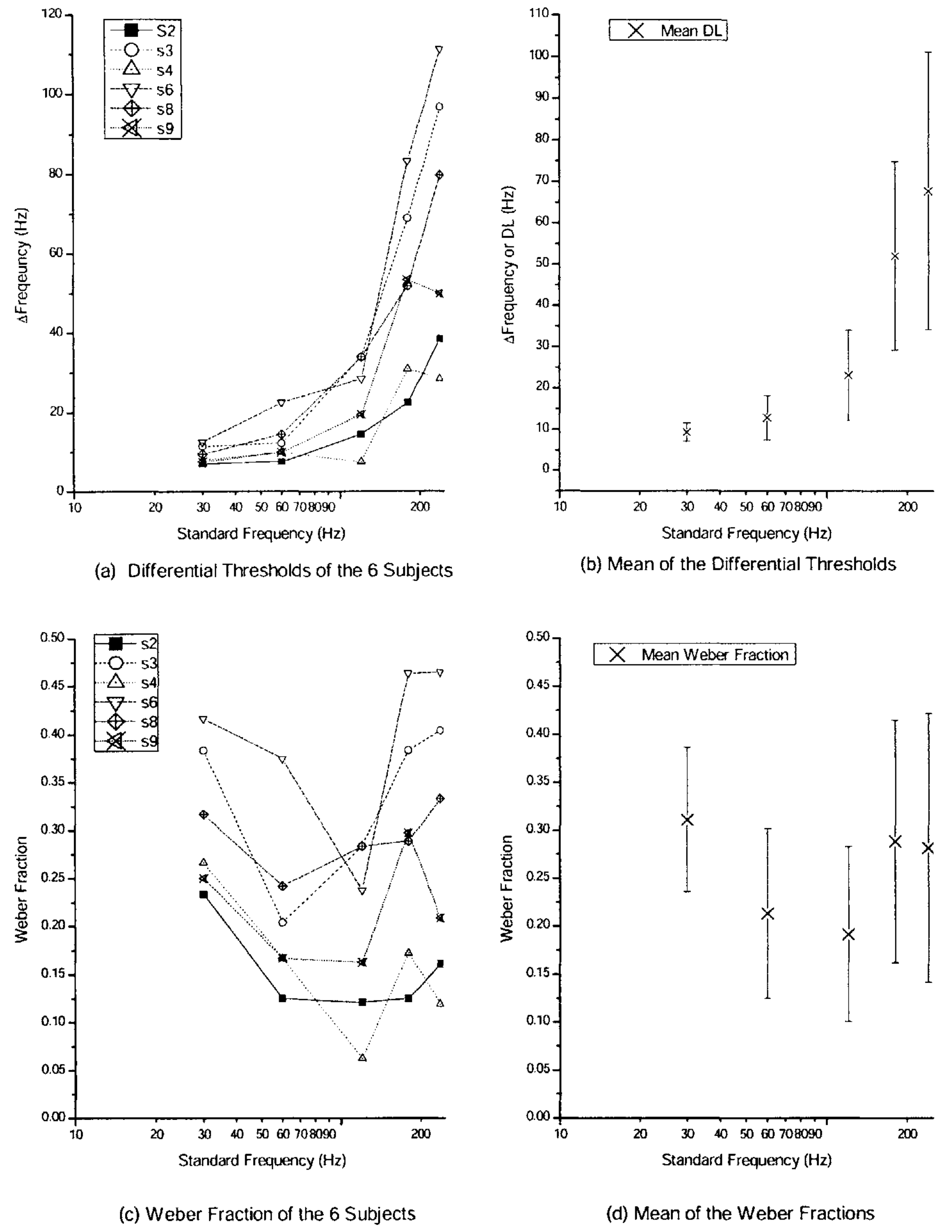
The transition point of an ascending session is called as L_u while L_l is the point where the responses change from "equal" to "different" in a descending session. The difference limen is defined as half the difference between mean L_u and mean L_l [28].

$$DL = \frac{1}{2}(\overline{L_u} - \overline{L_l}) \tag{5.1}$$

In addition, the changes in Weber fractions of the vibratory frequency are also obtained from the experimental results [28, 29].

$$Weber\ Fraction = \frac{\Delta\phi}{\phi} \tag{5.2}$$

where the ϕ term is the stimulus intensity. In this experiment ϕ correspond to the frequency and $\Delta\phi$ is DL.



(a) Differential Thresholds of the 6 Subjects

(b) Mean of the Differential Thresholds

(c) Weber Fraction of the 6 Subjects

(d) Mean of the Weber Fractions

Figure 5.3 The result of Experiment 4: Differential Thresholds and Weber Fractions

Figure 5.3 (a) represents the difference threshold of each subject as a function of frequency. At low frequency DLs are relatively small. As the standard frequency increases, the DLs increase rapidly. Although the DLs of Subject 4 and 9 rolled off a little bit at 240 Hz, it is in the range of standard error. The averaged result, therefore, is similar to Goff's data even if the intensity level of her experiment was different from mine. However, she didn't mention about the intersubject variability, which is important in this case [29, 30]. As described in the beginning of this section, I anticipated a dichotomous result for the two groups defined in Table 5-1. In addition, I expected the Weber fraction would increase as the standard frequency increases. However, the experimental results don't support my expectation. The variability of the individual DLs doesn't seem to be due to the difference between the subject groups, and besides, the Weber fractions in Figure 5.3 (c) level off or decrease as the standard frequency goes up to 120Hz. The Weber fractions are still changing more irregularly in the high frequency range around 240Hz.

5.3 Discussion

A spatial configuration of 4 contactors with two frequency components having different power levels was studied to investigate the possibility of transmitting various intermediate frequencies by changing the power ratio of the components. Based on the concept of selective stimulation, one component was set to 30 Hz frequency to stimulate the RA (Rapidly Adapting) afferents with the Meissner corpuscles while the other component was set to 240 Hz to stimulate the PC (Pacinian corpuscle-associated) afferents with the Pacinian corpuscles.

There have been a lot of researches about the neural coding mechanism used for signaling the frequency of vibratory stimuli generated by a single stimulator [6, 8, 9, 11, 13]. In those studies the experimenters could not help providing their subjects with a vibratory stimulus at each trial using just one frequency component. Even though Horch (1991) used the diharmonic stimuli to present two frequency components (120 and 240 Hz), the diharmonic component did not have as enough intensity to give the feeling of 240Hz as the fundamental frequency of 120 Hz [13]. He focused on the coding mechanism of the Pacinian channel range and argued the perceived frequency by the Pacinian corpuscles should be the harmonic mean of the components. As for the electrophysiology, although the neural signals from the monkeys' afferents and cortical area for each mechanoreceptor have been recorded and analyzed for the one stimulator case changing the frequency and amplitude, the result from physiology could not completely explain the psychophysical experimental results which showed changes in pitch with increase in the vibrating amplitude [8, 9, 11]. As the encoding mechanism for vibrotactile frequency of the whole range is not fully revealed yet even for one contactor case, a possible analysis of tactile perception of spatially distributed stimuli might be to hypothesize a model explaining the experimental results.

5.3.1 Ratio code and suppression model

For a ratio code analysis, we should know the activation levels of mechanoreceptive fibers in the finger tip, and thus I adapted the electrophysiological data from Talbot *et al.* (1968) even though they used monkey's hand assuming what moneys and humans felt with their hand was the same [6, 8]. Using their data, the number of the RA and PC fibers which were entrained following the stimulus with a one-to-one manner was obtained at two vibratory frequencies (30 and 200 Hz) assuming the neural activation trend at 240Hz is not significantly different from that at 200Hz. This method was used before by Morley and Rowe, who failed to support the ratio code mechanism based on 30 and 150Hz because the results of psychophysical experiments were not so they expected. They predicted the perceived frequency would decrease if the ratio code worked well, but three quarters of their subjects showed the opposite responses [6]. However, my experimental results might be explained partly by this ratio code because the perceived frequencies in Experiment 1 were much lower (below 150Hz) at the highly suprathreshold amplitude than the component frequency of 240 Hz.

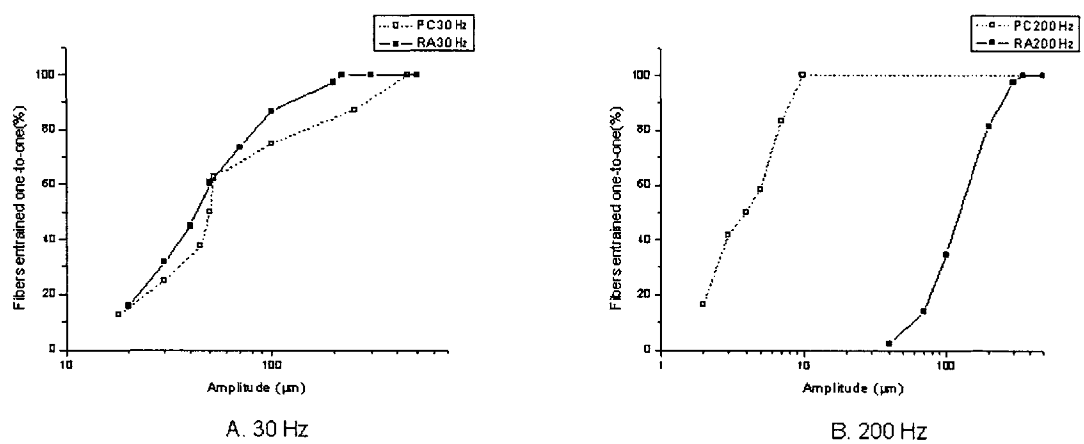


Figure 5.4 The effect of amplitude on the recruitment of RA and PC fibers. The data points are the percentage of the number of fibers, which are firing with the same frequency of the vibrating frequency, as a function of the amplitude. The data for these plots were adapted from Fig.22 (RA) and Fig.24 (PC) of Talbot *et al.* [6, 8]

From the results of Experiment 2, the subjects can easily discriminate between a pure-tone and a compound waveform even if both of them give the same power level. This might mean the subjects felt the individual components separately. These individual components, however, might be already affected by the amplitude based on the ratio of RA and PC fibers according to their own best frequency. For instance, let's thinks of the perception of CW5 in Table 4-1 which has two components: 113μm with 30Hz and 69.3μm with 240Hz. Seven of our ten subjects perceived the CW5 as low as 120Hz, which can be explained by the ratio code as follows. First of all, as seen in Figure 5.4A, at low frequency the ratio of PC to the RA does not change much even though the amplitude is increasing. Therefore, the subjects should feel the 30 Hz component in CW5 as it is. In contrast, at high frequency the ratio of PC to RA decreases significantly because the number of RA firing at the stimulating rate increases with the amplitude while the PC already reaches the saturation after 10μm (Figure 5.4B). Consequently the perceived pitch should decrease remarkably, which agrees with the experimental results.

However, the range of amplitude of 240 Hz component for the other compound waveforms was between 40μm and 65.3μm which gives just small changes of the activation level of RA, so the difference in perceived frequency between the five compound waveforms should be ignorable. According to this interpretation, it seems to be reasonable that subject 1, 2 and 3 didn't show much different responses to the change of the compound waveforms. However, in order to explain the generally increasing trends in the results of Experiment 1, we still need to hypothesize another mechanism for spatially distributed stimuli. As the power ratio of the high frequency to the low frequency increased from 1/3 to 3, the overall perceived frequency in general increase up to 120 Hz which is one of the perceived frequency components. If one component has a dominant power level, the overall pitch might be biased toward the perceived frequency of that component. In other words, the high power component might suppress the feeling of the other low power stimuli. Therefore, the perception of spatially distributed stimuli might depend on the power ratio distribution of the all components.

To sum up, the steps in this model as follows.

a) The subjects felt the individual components (Experiment 2).
b) The perceived pitch of each component followed the ratio code mechanism (Hypothesis).
c) The power ratio determined the bias of the overall feelings (Experiment 1).

5.3.2 Irregularity

Although the ratio code and suppression model explained well the general trends of the experimental results, the inter- and intra-subject variability found in the Experiment1 makes strong conclusions difficult. The spatial resolution of the tactile display among others might cause the irregular responses of the subjects. The original idea about the haptic color would work if people feel a compound tactile element as one stimulus. It is like we never recognize a pixel in the computer monitor. In the Experiment 1, all the subjects said that it was too hard to match two apparently different stimuli, and in Experiment 2 they easily discriminated between the pure-tone and the compound waveform. Therefore, the spatial resolution of the tactile display might be not sufficient to test the possibility of the haptic color idea even if that idea would be valid in nature. In addition, the amplitude was controlled by the open-loop, so the actual deflection of the actuators might be not the same as purposed to present in spite of the calibration.

The inhomogeneous factors in the experimental procedures would affect the variable responses of the subjects. Because the tactile display has been developed to provide tactile sensation with a free user in the virtual environment, the experiments were done without any fixture for binding the finger or hands. In fact, the actual displacement of the actuator depends on the pressing force. Although I used a force sensor on the nail to keep the pressing force constant, the actual pressure acting directly on the actuator should be different from subject to subject and even for the same subject. What is more important is that the feeling of the compound waveforms is changing even with the position of the finger pad stimulated.

The sensation levels that the subjects feel depend on their own sensitivity or the thresholds. For convenience, I assumed the intersubjective difference in the sensation threshold is not much and used the Verrillo's data without measuring the threshold of each subject [32]. The subjects in my experiments, therefore, felt slightly different sensation level even for the same amplitude, which might be a minor effect on the results.

What is the most difficult to interpret is the effect of the other afferents firing at different rate even though they are in the same mechanoreceptor group. For example, there might be two PC afferent groups: one is entrained at 240Hz and the other is entrained at 30Hz because of the adjacent contactors. RA fibers also have two kinds of firing rates. When the ratio code was included in the model for the experimental result, I assumed the influence of the adjacent stimuli would be small and the perceived pitch of one vibratory frequency would depend on the PC fibers and RA fibers which were firing at the same rate as stimulators. Morley and Rowe also focused on the number of the fibers activated with one-to-one manner even though there were many other fibers firing at lower frequencies than the stimulating rate [6]. If the overall distribution of the active population would be integrated in the cortical level, we need more complicated electrophysiological experiments using the spatially distributed stimuli.

6 Conclusion

6.1 Factors in texture discrimination

The 4 kinds of mechanoreceptors underneath the glabrous skin have their own best responsive frequency range. In the texture judgment tasks, the subjects showed higher correct answer rate near the best frequencies than in other intermediate ranges. Meissner corpuscles and Merkel disks innervated densely on the finger tip might play a major role in the detection of small scale features vibrating in low frequency (1-40Hz). The trace of correct answer rate showed the local maxima around 1 and 30Hz which are the best frequencies of those mechanoreceptors. However, as the frequency increased to high enough (>200Hz), the correct answer rate rolled off even though 250Hz is the best frequency of the Pacinian corpuscles. This can be accounted for by the bad spatial resolution of the Pacinian corpuscles. The Pacinian corpuscles have the relatively large volume and lower innervation density than the other mechanoreceptors even if they are the most sensitive receptors of high frequency.

In addition, the experimental results show that the subjects obtained information about the vibrating features from not only the temporal cue but also the energy of the stimuli. On the basis of the characteristics of the Pacinian corpuscles, the spatial acuity of PC should be bad because of their volume and large receptive field. But the experimental results showed that the correct answer rate increased slightly at high frequency. However, when we used the same power level for all samples, the correct answer rate was low as we expected. Therefore, the power level might be the intensity of vibratory stimuli. To sum up, the perception of spatially distributed stimuli would depend on the characteristics of the mechanoreceptors and the stimulating power level.

6.2 Tactile perception of the compound waveforms

Expressing colors in computer graphics is based on the characteristics of human color vision system which depends on the activation of cone photoreceptors with different spectral sensitivities. As an analogy between color vision and tactile perception, a spatial configuration of the multiple contactors distributed in the same plane was proposed to deliver the intermediate feelings using the compound waveform defined as a sinusoidal stimulus which is presented by four contactors vibrating with 30Hz and 240Hz. The spatial configuration of the four contactors was determined by replication of a pixel in computer graphics as seen in Figure 4.4. The two frequencies of the tactile element are the most sensitive frequency range of the Meissner corpuscles and the Pacinian corpuscles, respectively. The five compound waveforms, which have different power ratios of the two components but the constant total power, were matched to an intermediate pure tone by 10 subjects who didn't show different ability in an adjusting task. In order to give the same stimuli to each subject who has different skin biomechanical properties and finger force, calibration of the tactile display was customized to each subject. The experimental results showed that the perceived frequency in general increased from about 30 Hz to 120 Hz with the increase in the power ratio of the high frequency component to the low frequency even if there was inter- and intra subject variability. Two follow-up experiments were tried to figure out the causes of the variability, but there didn't seem to be statistically significant difference in DLs and matching ability of the chosen 6 subjects.

After the adjusting task, the same subjects discriminated between the compound waveforms with the pure-tone they had matched to the compound waveform. In discrimination tasks based on the *same-different paradigm*, the sensitivity value d' of the most subjects was over 4.0, which means they easily detected the difference between two stimuli. Therefore, it might be difficult to make people feel a compound stimulus as if it were an intermediate pure tone, at least using this spatial configuration of the tactile display with resolution of 1.8 mm.

6.3 Ratio code and suppression model

Although the subjects showed almost perfect discrimination ability and thus the haptic color idea might be not working at least in the experimental conditions tested, the general trends in adjustment tasks make it possible to validate a model for neural encoding mechanism of information about vibratory frequency. Morley and Rowe (1990) couldn't find a strong experimental evidence of the ratio code in which the representation of frequency is based on the relative activation the PC and RA sensory fibers [6]. Roy and Hollins (1998) modified the ratio code based on the P, NPI, and NPIII activation levels and confirmed the model for three of four subjects [11]. While most experiments so far were carried on using a single contactor vibration system, the present study is based on the tactile display with multiple contactors.

The electrophysiological experiment data were derived from Talbot *et al.* to obtain the relative activation of PC and RA fibers at 30 and 200 Hz as a function of the vibratory amplitude [6, 8]. According to the ratio code mechanism, the decreasing ratio of PC to RA as the amplitude increases at 200 Hz should lead to a significant drop in the perceived frequency. On the other hand, at 30 Hz, the perceived frequency should change little with the stimulating amplitude because the ratio does not change much with the amplitude. The results of Experiment 1 confirm the prediction because the perceived frequencies of CW5 (5^{th} sample of the compound waveform in Table 4-1) are about 120 Hz which is much below the 240 Hz component. And the perceived frequency of CW1 is also close to 30Hz.

The fact that the perceived frequencies much lower than the component frequency might support the ratio code, but the increasing trends of them with the increase in the power ratio of the high frequency component need additional mechanism for signaling the spatially distributed stimuli. As for the effect of the power ratio on the perception of vibratory stimuli, a suppression model was proposed in which the component with relatively high power level determines the overall sensation. In Experiment 1, as the power ratio of the high frequency to the low frequency increased from 1/3 to 3, the overall perceived frequency in general increased up to 120 Hz which is the perceived frequency of the high frequency component. If one component has a dominant power level, the overall pitch might be biased toward the perceived frequency of that component. In other words, the high power component might suppress the feeling of the other low power stimuli.

In conclusion, tactile perception of spatially distributed vibratory stimuli depends on the relative activation level of the mechanoreceptors corresponding to the component frequencies and the power ratio distribution of them. In addition, the spatial configuration of four contactors for realizing a tactile element might need another tactile display or experimental apparatus with higher resolution even if the analogy of tactile perception to color vision is assumed valid over a fundamental part (0 ~ 300 Hz) of the frequency range of vibrotactile sensation.

Appendix A

Experiment Procedure

1. Put on the earphone. Rest your index finger of left hand on the tactile display.(Use right hand to control the computer mouse)

2. Click **Random Sample** to get a target stimulus for adjustment. All stimuli will be presented for 1 second.

3. Estimate the rough range of frequency of the given stimulus and click one button out of **Slow**, **Medium** and **Fast**.

4. Adjust the frequency to what you felt in Step 2 using **Up** or **Down** button in the box Frequency Adjustment. If you want to repeat the given stimulus and compare it with the adjusted, use the buttons in the box Comparison. Note that you must use your "Middle finger" for replaying the **Given** stimulus, whereas you use "Index finger" for replaying the **Adjusted**. When you think you've made the closest adjustment at last, use your Index finger for the given stimulus as well, but with 10 second interval. If you are comfortable with the match, go to the next step. If not, keep adjusting.

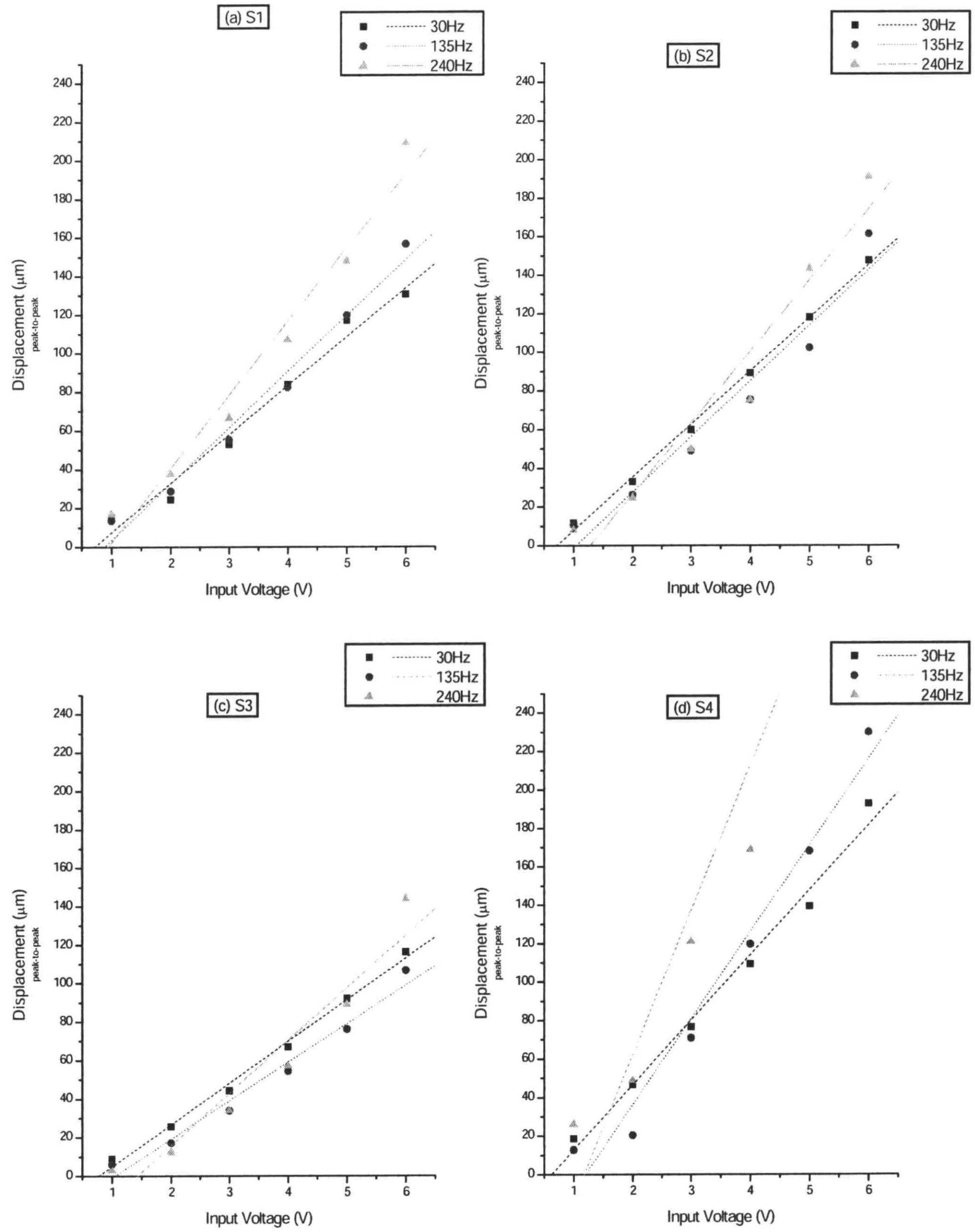
5. After the adjusted frequency is as close a match as possible to the given stimulus, adjust the amplitude by **Up** or **Down** button in the box Amplitude Adjustment. Use the buttons in the box Comparison in the same fashion in step 4. Do not return to step 4.

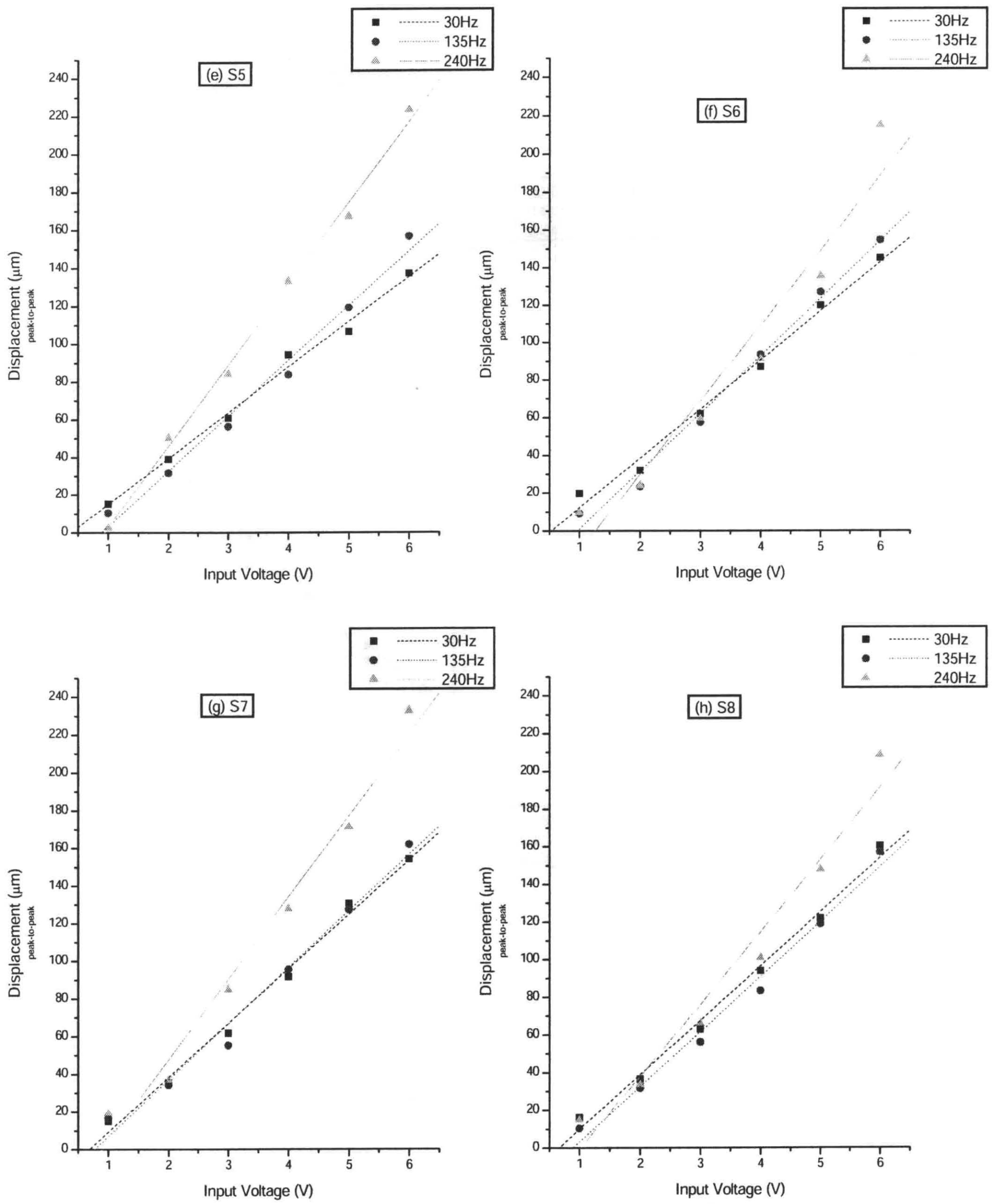
6. Click the **Save** button to confirm the adjustment. This completes the one trial.

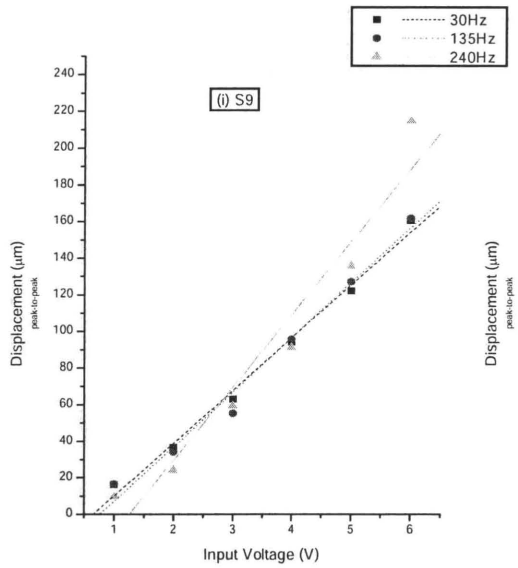
7. Repeat step 2-6 for a total of 15 trial

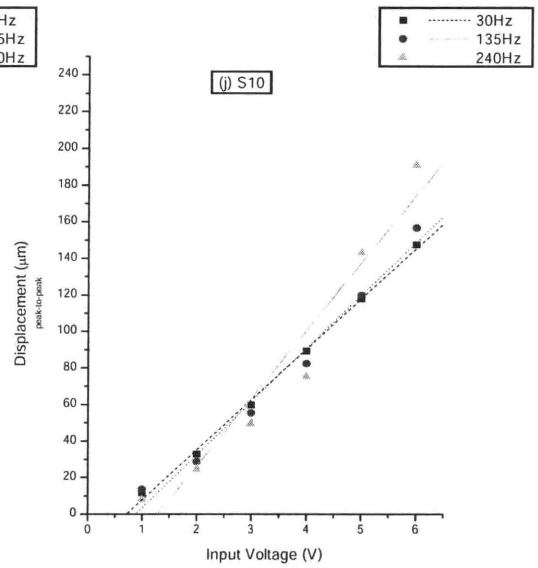
Appendix B

Actual skin displacement




30Hz
135Hz
240Hz
(e) S5
(f) S6
(g) S7
(h) S8
Displacement (μm) peak-to-peak
Input Voltage (V)


30Hz
135Hz
240Hz
(i) S9
Displacement (μm) peak-to-peak
Input Voltage (V)


30Hz
135Hz
240Hz
(j) S10
Displacement (μm) peak-to-peak
Input Voltage (V)

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