MEASUREMENT OF VIBROTACTILE THRESHOLDS OF NORMAL CHILDREN

by

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ABSTRACT

In this study, the vibrotactile thresholds of children (ages between 8 and 11) were measured at several frequencies, and compared to the vibrotactile thresholds of adults (ages between 21 and 27) at 40 Hz and 250 Hz. Also, the thresholds of Non-Pacinian I (NPI) channel of children were measured at 40 Hz.

Since Pacinian (P) channel and NPI channel have similar thresholds at 40 Hz, a forward-masking procedure was used to elevate the threshold of P channel. Results were compared to NPI channel thresholds of adults at 40 Hz. To enable comparison with population models of mechanoreceptive fibers in the literature, the studies were performed using the terminal phalanx of middle finger and no contactor surround was used. Thresholds were measured using a two-interval forced-choice paradigm, in order to ensure that the measurements were independent of the subject's criterion.

No statistically significant differences were found between the absolute thresholds of children and adults at 40 Hz and 250 Hz. For NPI channel thresholds, children and adults' data were found to be marginally different. However, more data are needed to reach a firm conclusion. Moreover, the masking functions of children at 250 Hz were obtained. The threshold shifts increased as masking stimulus levels were increased. The results were discussed in relation to previous studies in literature.

Keywords: Vibrotactile sensitivity, psychophysical channels, aging

NORMAL ÇOCUKLARDA DOKUNMA DUYUSUNUN TİTREŞİMSEL DUYARLILIĞININ ÖLÇÜLMESİ

ÖZET

Bu çalışmada 8-11 yaşları arasındaki çocukların dokunma ile ilgili titreşimsel eşik değerleri çeşitli frekanslarda ölçülmüş, ve yaşları 21 ile 27 arasında değişen yetişkinlerin 40 Hz ve 250 Hz'deki titreşimsel eşik değerleriyle karşılaştırılmıştır. Bunun yanında, çocuklarda 40 Hz'de Pacini Olmayan I. Dokunma kanalının (NPI) eşik değerleri de ölçülmüştür.

Pacini (P) kanalı ve NPI kanalı 40 Hz'te yakın eşik değerlerine sahip olduklarından, P kanalının duyarlılığını azaltmak için ön maskeleme tekniği kullanılmıştır. Sonuçlar, yetişkinlerin 40 Hz'deki NPI kanalı eşik değerleriyle karşılaştırılmıştır. Deneyler, mekanik algılayıcıların literatürdeki populasyon modelleri ile kıyaslama yapılabilmesi için orta parmağın üst boğumunda ve kontakt ucu çevreleyicisi kullanılmadan yapılmıştır. Eşik değerleri, deneğin seçim kriterinden bağımsız ölçüm yapılabilmesi için, iki aralıklı zorlanmış seçim paradigması kullanılarak ölçülmüştür.

40 Hz ve 250 Hz frekanslarındaki mutlak eşik değeri ölçümlerinde çocuk ve yetişkin grupları arasında istatistiksel olarak anlamlı bir fark bulunmamıştır. NPI kanalı eşik değeri ölçümlerinde ise çocuk ve yetişkin grupları istatistiksel olarak biraz farklı bulunmuştur. Fakat, daha kesin bir yargıya varabilmek için daha çok deney yapılması gerekmektedir. Ayrıca, çocukların 250 Hz'deki maske fonksiyonları çıkarılmıştır. Maske uyarı seviyesi arttıkça eşik değerleri de yükselmektedir. Çalışmanın sonuçları literatürdeki diğer çalışmalarla karşılaştırılarak tartışılmıştır.

Anahtar Kelimeler: Titreşimsel duyarlılık, psikofiziksel kanallar, yaşlanma

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

DCN	Dorsal Column Nuclei
FA	Fast Adapting
FFT	Fast Fourier Transform
LED	Light Emitting Diode
NIH	National Institute of Health
NP	Non-Pacinian
P	Pacinian
PC	Pacinian Corpuscle
RA	Rapidly Adapting
RF	Receptive Field
SA	Slowly Adapting
SL	Sensation Level

LIST OF SYMBOLS

A_{masker}	Amplitude value of the masking stimulus
$A_{threshold}$	Amplitude value of the threshold
P	Probability value in statistical test "t-test"
α	Level of significance of the statistical test

1. INTRODUCTION

Tactile perceptions are derived from information provided by mechanoreceptors innervating the skin, and in some cases, subcutaneous tissues. A mechanoreceptor is the end organ that actually transduces mechanical energy into electrochemical energy, forming a neural signal. The skin is innervated by sensory nerve fibers possessing distinct and specialized response properties. Each fiber type is associated with a morphologically identified end organ.

One way of measuring tactile sensitivity is to determine the smallest amplitude of vibration of the skin that can be detected by an observer. Vibrotactile thresholds depend on stimulus factors such as the locus of stimulation, the size of the stimulated skin area, the duration of stimulus and the frequency of vibration. Using sinusoidal stimuli in which the amplitude and frequency of displacements can be independently controlled, several investigators determined sensory threshold at various frequencies for the glabrous skin of the human hand [1].

It is well known that advancing age is associated with diminished functioning of sensory systems. The cutaneous senses are no exception, as many studies have documented a loss of tactile sensitivity with increasing age [2-5]. Furthermore, the sensitivity loss is not uniform across all frequencies of vibration [2].

In early works, it was shown that the tactile sensitivity decreases with age [2-5]. The purpose of this study is to obtain a frequency-threshold characteristics for children between ages 8 and 11, and compare the children's thresholds with adults' thresholds at certain frequencies (40 Hz and 250 Hz). Moreover, the Non-Pacinian I channel thresholds are measured at 40 Hz and compared to adults' thresholds. Contrary to previous studies, the measurements were done at the fingertips of the subjects, and no contactor surround was used, so that the results could be used as a reference in modeling studies or compared to results of physiological experiments.

2. THEORY

2.1 Somatosensation

Somatosensation is composed of sensations imposed on the body both from outside environment and internal environment of the body as well as proprioceptor information about the body movement. Somatosensation is a multimodal sensory experience because somatic perceptions arise as a result of the activation of tactile, thermal and the receptors of noxious stimuli.

The peripheral basis of tactile sensations arises by activation of sensory receptors located in the skin that are responsive to mechanical stimuli. These receptors are called mechanoreceptors. A mechanoreceptor is the end organ of a nerve that actually transduces mechanical energy into electrochemical energy, thus forming the neural signal.

2.2 The skin

The sensory receptors responsible for tactile sensations reside in the skin, a multilayered coating organ covering the entire body, inside and out. The skin functions in thermoregulation, protection, metabolic functions and sensation. Sensory perception is critically important in the avoidance of pressure, mechanical or traumatic forces and extremes of temperature. Numerous specialized structures are present in the skin to detect various stimuli.

The skin is a highly complex structure, it includes sensory receptors and nerve fibers, blood vessels, sweat glands, and other specialized components such as hair, hoofs, claws, and nails. Skin can be classified into three types, glabrous or hairless skin characterized by the skin of the palm; hairy skin which includes hair; and mucocutaneous skin which borders the entrances to the body’s interior. These three types of skin have differences in their mechanical properties. These mechanical properties also vary as a function of body locus, age, gender, and species [6-9].

Skin is composed of an outer layer (epidermis) and an inner layer (dermis). The dermis separates the epidermis from the underlying muscle, ligaments, and bone. Both the dermis and epidermis are formed by strata having specific characteristics. (See Figure 2.1) [10]

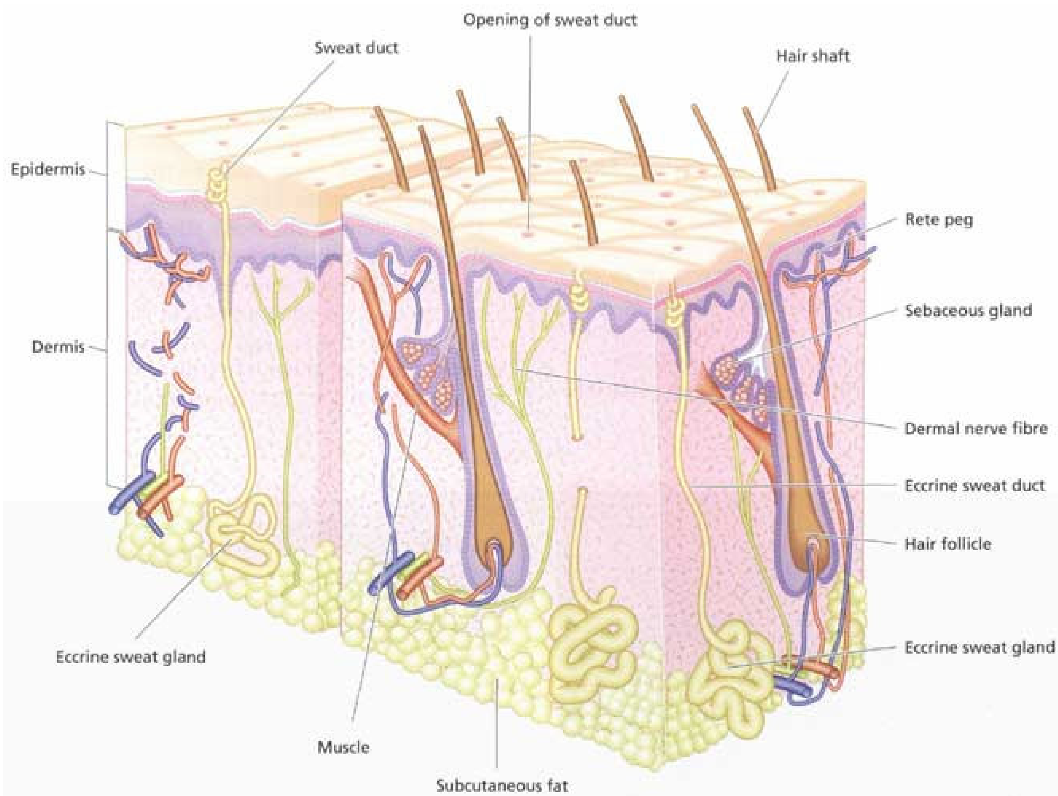

Figure 2.1 – The three-dimensional structure of the skin: (left) the thick hairless skin of the palm of the hand, (right) the thin hairy skin of the forearm [10].

The epidermis consists of stratified squamous epithelial cells in various stages of differentiation. The outermost layer, stratum corneum, is composed of dead cell tissue of a tough, horny nature. Epidermal cells are made in the lowest layer, the stratum germinativum (or basal layer), and migrate outwardly, reaching the stratum corneum where they die. The epidermis contains no blood supply.

The dermis is composed of connective tissue and elastic fibers floating in a semifluid, nonfibrillary amorphous mixture called the ground substance. Also embedded in the ground substance are fat cells, smooth muscle, sweat glands, and a profuse blood and lymphatic supply. The dermis is composed of two layers, the papillary layer and the reticular layer.

2.3 Mechanoreceptors

The peripheral basis of tactile sensations arises by the activation of sensory receptors, located in the skin, that are responsive to mechanical stimuli. These sensory receptors are typically complex in structure, but the basic organization is that of a neuron that has unmyelinated terminal ending responsible for mechano-electric conversion.

Neural activity arising in the spinal nerves as a result of mechanical stimulation of the mechanoreceptors is passed across the dorsal root ganglion and enters the spinal column, where it takes one of the three routes. Following the first pathway, the activity is directly passed upward in the spinal column via tracts called the dorsal columns. These bilateral dorsal columns are myelinated fiber tracts in posterior region of the spinal cord. It is a direct pathway of activity to brain structures called the dorsal column nuclei (DCN), located in the brain stem. Since it is a direct pathway, no synapse is present between the site of mechano-electric conversion and the dorsal column nuclei. The synapses are located within the dorsal column nuclei and the projection neurons from the dorsal column nuclei are considered the second-order neurons of the somatosensory system. These secondary neurons form a pathway called the medial-lemniscal system, which projects directly to thalamus. The second pathway for the activity arising in the mechanoreceptor originates in the synaptic regions within the spinal cord, the central grey matter. Via a single synapse, the neural activity is relayed towards the brain by a pathway called the spino-cervical-thalamic tract. This pathway originates in spinal column, projects to the cervical nucleus and after synapsing there, the projection neurons merge with the dorsal-column/medial lemniscal system, subsequently synapsing in the thalamus. The third pathway does not go higher, central nervous system regions like thalamus, but operates at the spinal-cord level to control the responses of motor neurons. (See Figure 2.2) [11]

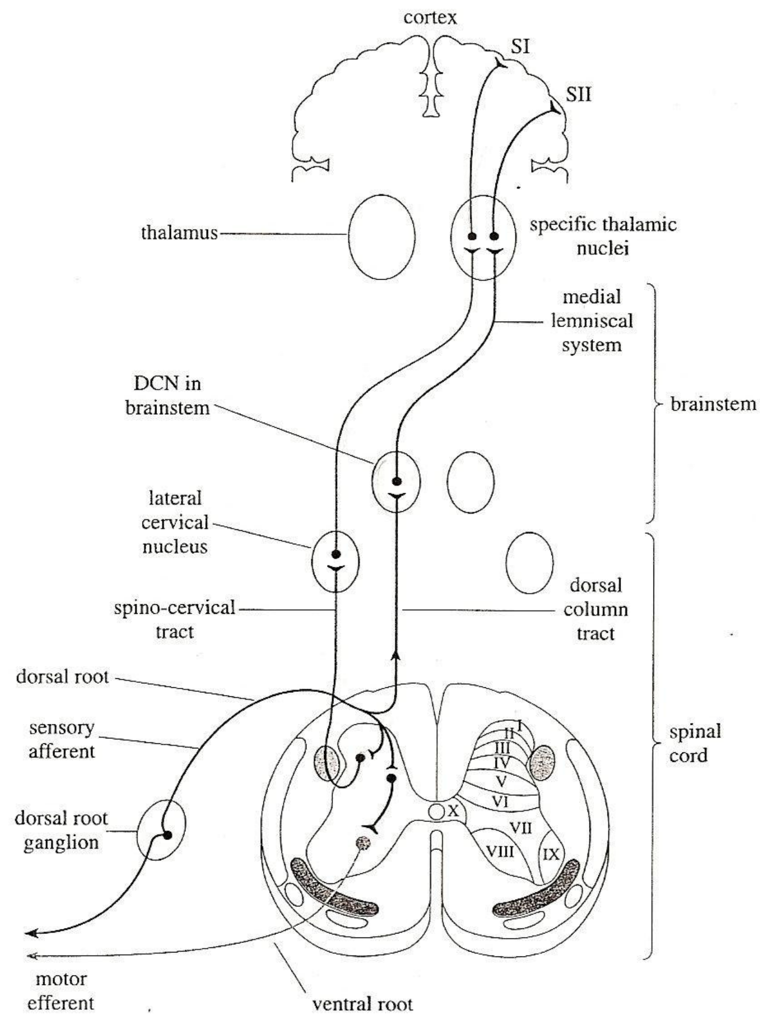

Figure 2.2 – An overall view of the tactile pathways. [11]

Information arising from the mechanoreceptors goes to specific regions within the thalamus, specifically the posterior and ventral-medial aspects. Processing of information occurs at the level of the thalamus, and its output goes to primary and secondary somatosensory cortex.

Mechanoreceptors come in a variety of shapes and forms, and may or may not have non-neural elements attached or adjacent to the nerve terminations. (See Figure 2.3) [12] The non-neural elements, referred to as accessory structures, are thought to participate in selective filtering of mechanical stimuli [13], to allow for tropic influences [14], and to regulate the ionic environment around the nerve ending [15]. One major class of endings with accessory structures are encapsulated endings (Pacinian corpuscles, Ruffini capsules and Meissner corpuscles). A second class of endings has accessory structures to which they are attached (Merkel cell-neurite complex, Iggo corpuscle, circumferential and palisade fibers on the shaft of hairs). Another major class of endings in the skin is the free nerve endings, which do not have accessory structures.

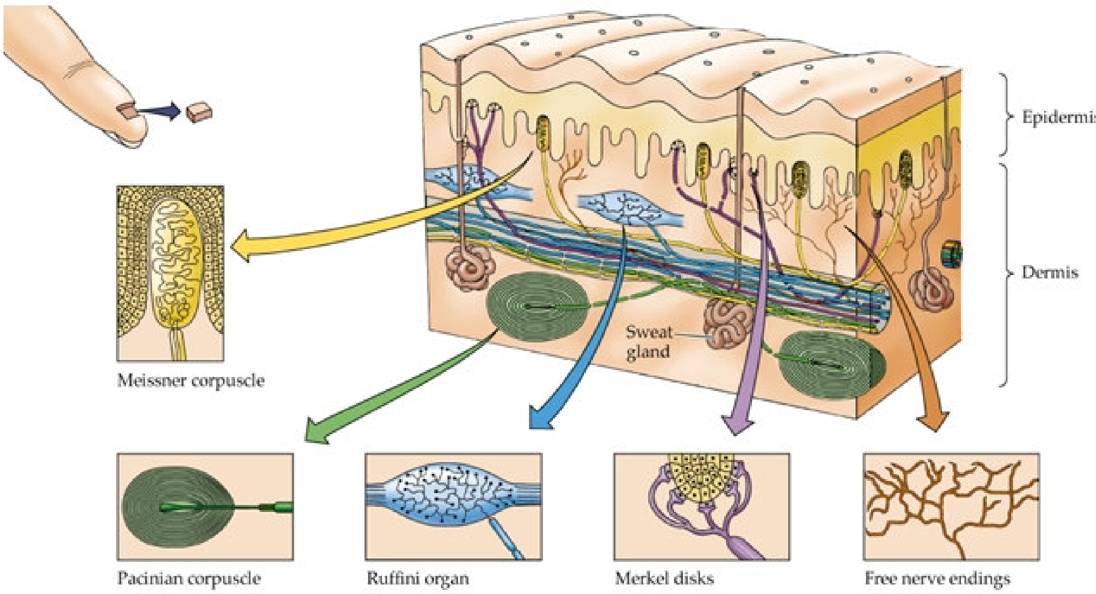

Figure 2.3 – The anatomy of glabrous skin showing receptor locations. [12]

The mechanoreceptor's neural component typically consists of an unmyelinated nerve terminal continuous with a myelinated nerve fiber, which has its soma in the dorsal root or trigeminal ganglion. The unmyelinated nerve terminal is the region where mechanotransduction takes place, whereas the myelinated nerve fiber is capable of transmitting action potentials.

2.4 Mechanoreceptors innervating the glabrous skin of the hand

Four types of mechanoreceptive afferents innervating the glabrous skin of the human hand have been identified (See Figure 2.4) [16-22]. Two principal features define these four types: adaptational properties and receptive field size. Two of the afferent types are slowly adapting (SAI and SAII), and two are fast adapting (FAI (or RA) and FAII (or PC)).

The adaptation means the rate of decline in action potential firing rate in response to ramp-and-hold-like stimulus. There are two subclasses of fast adapting and slowly adapting mechanoreceptors. FAI mechanoreceptors respond mostly to the ramp portion of the stimulus while FAIIs only respond to the corners of the ramp-and-hold stimulus. SAIs, on the other hand, respond not only to the ramp portion of the stimulus, but also to the hold portion with an irregular firing pattern. Finally, SAIIs display a more regular firing rate and also have spontaneous activity, this activity occurring in the absence of controlled stimulation.

The receptive field (RF) of a mechanoreceptor is the area of the skin that, when stimulated, will generate a response in that sensory neuron. The precise boundary of this area will depend upon the intensity of the stimulus used. But with any specific stimulus, the SAI and FAI afferents will be activated within a much smaller area of skin than the SAII and FAII afferents, which is to say that the type I fibers have smaller receptive fields than type II fibers.

Although adaptation and receptive field size are defining characteristics of the afferent types, there are other distinguishing features. Each of these four afferent types has been identified with a specialized structure within the skin: the FAI afferent with the Meissner corpuscle, the FAII afferent with the Pacinian corpuscle, the SAI with the Merkel cell-neurite complex, and the SAII with the Ruffini endings [1].

Another important property is the innervation density of these receptors in the hand. Type I afferents (FAI and SAI) exhibit a large gradient of innervation; the greatest density found in the fingertips, becoming more sparse in the proximal direction. The Type II afferents show only a slight difference in density across the hand [23].

The basic properties of these afferents are summarized in Figure 2.4. [11]

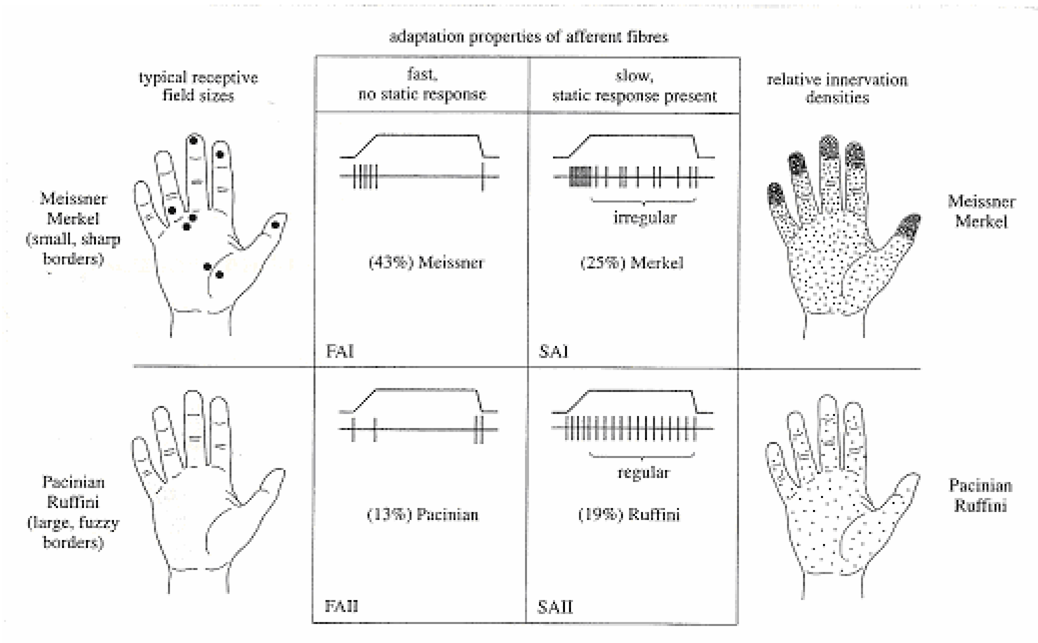

Figure 2.4 – Characteristics of the four types of mechanoreceptive afferents that innervate the glabrous skin of the human hand. These characteristics are found using ramp-and-hold stimuli. [11]

2.5 Psychophysical Channels and Vibrotactile Thresholds

Psychophysics is the scientific study of the relation between stimulus and sensation. It consists primarily of investigating the relationships between sensations in the psychological domain and stimuli in the physical domain. Central to psychophysics is the concept of a sensory threshold. The absolute threshold or stimulus threshold is traditionally defined as the smallest amount of stimulus energy necessary to produce a sensation. In more modern and less subjective terms, the absolute threshold or stimulus threshold is the smallest amount of stimulus energy necessary to achieve some criterion level of performance, such as correct responses 75% of the time, in a stimulus detection task.

Development of the theory of signal detection and the refinements of methods for directly scaling sensory magnitude have greatly broadened the applicability of psychophysics far beyond the original problems of measuring sensory thresholds. Modern psychophysics can be credited with contributions to the solution of problems in such diverse realms as sensory processes, memory, learning, social behavior and esthetics.

Using vibratory (sinusoidal) stimuli in which the amplitude and frequency of displacements can be independently controlled and precisely specified, several investigators determined sensory threshold at various frequencies for the glabrous skin of the human hand [1].

Many psychophysical, physiological and anatomical experiments have been performed to determine additional relationships among the four physiologically defined fiber types in glabrous skin to the psychophysically defined threshold-frequency characteristic. Based on these studies, Bolanowski, Gescheider, Verrillo and Checkosky (1988) [24] proposed that there are four distinct psychophysical channels contributing to taction in the glabrous skin, each channel being mediated by a specific fiber type (See Figure 2.5) [25]. The threshold-frequency characteristics of the four channels were determined by means of manipulating stimulus parameters, such as the frequency and amplitude of the vibration, probe or contactor size, stimulus duration, skin-surface temperature, and the application of various masking techniques [1].

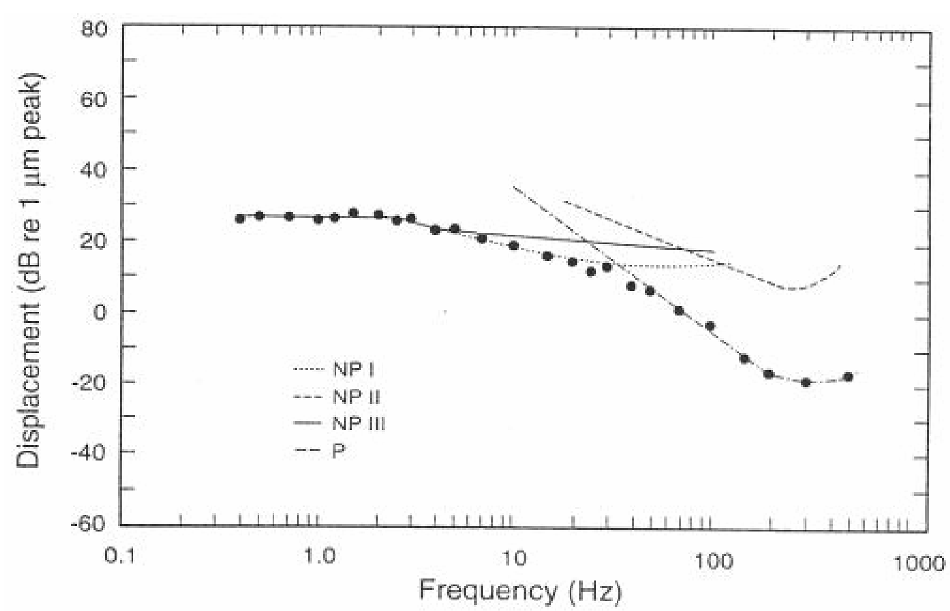

Figure 2.5 – Vibrotactile thresholds as a function of frequency (filled data points). The curves are frequency characteristics of each of four tactile information processing channels. [25]

The model proposes that each psychophysical channel consists of specific end organs innervated by select groups of peripheral nerve fibers, the isolated activation of which can produce unique unitary sensations. Two major tenets of the model are that stimuli at threshold levels are signaled by the channel that is the most sensitive, and that suprathreshold sensations are the result of a combination of the neural activity transmitted by all activated channels. Not all of the four channels need be activated for a suprathreshold sensory experience. Indeed, for certain suprathreshold conditions only one or two channels will be activated [26, 27]. In that instance a specific tactile sensation will result, albeit of a quality different from that experienced if all four channels are activated. Another important point is that the model does not intrinsically require the existence of four channels. The model simply proposes that the sense of touch utilizes information being transmitted by separate, independent channels. Integration of the activity arriving over the different channels must ultimately be combined to provide a unified perception. The model proposes that the psychophysiologically defined channels, their end organ-nerve fiber substrates, their respective unitary sensations and the nominal frequency range over which they operate at threshold levels are:

1. Pacinian (P) channel, mediated by Pacinian corpuscles and PC fibers, producing the sense of vibration in the frequency range of 40-500 Hz;

2. non-Pacinian I (NPI), mediated by Meissner corpuscles and RA fibers, producing the sensation of flutter in the frequency range of 2-40 Hz;

3. NPII, mediated by Ruffini end organs and SA Type II fibers, producing a buzz-like sensation in the frequency range of 100-500 Hz;

4. NPIII, mediated by Merkel cell-neurite complexes and SA Type I fibers, producing the sensation of pressure on the frequency range of 0.4-2 Hz.

3. METHODS

The absolute tactile sensitivities and the NPI channel thresholds of normal children between ages 8 and 11 were measured in psychophysical experiments. Unlike most of the previous experiments in the literature, stimulus was applied to the fingertip, and contactor surround was not used.

3.1 Subjects

Three female and six male normal subjects were used, whose ages ranged between 8 and 11. The subjects did not have any neurological diseases that may interfere with the procedures.

Subjects were paid volunteers, who were recruited locally. They were tested with the permission of their parents, and informed consents were obtained. The experiments posed no harm to the children and they were free to quit the experiments any time if they wanted. The experiments adhered to National Institute of Health (NIH) ethical guidelines for testing human subjects and were approved by the Ethics Committee for Human Experiments in Boğaziçi University.

3.2 Apparatus

The experiments were performed in a booth insulated from sound and vibration. The stimuli were bursts of sinusoidal displacements produced by a mechanical shaker (Ling Dynamic Systems). The shaker was connected to a rail system mounted on a table and was able to move in three dimensions by use of X-Y-Z manipulators (Edmund Industrial Optics). The sinusoidal vibrations were produced by computer with an analog output card (IOTECH). The amplitude of the vibrations was adjusted by a high-precision digital attenuator (Tucker-Davis Technologies). The mechanical shaker was driven by use of a power amplifier (Alesis). The vibrations were measured by a linear-variable displacement transducer (Schaevitz Sensors) and measured by FFT analysis on an oscilloscope (Tektronix).

The stimuli were applied to the terminal phalanx of left middle finger. In order to prevent movement of subject's finger during the experiments, the finger was molded in modeling clay. Also, the fingertip was monitored by a camera mounted on the table, and the experiment was stopped in case of a movement.

The shaker generated noise at high frequencies (>200 Hz), so, a continuous white noise was presented to the subjects on headphones to mask the shaker's noise.

The response of the subject was obtained by a custom-made response box, which had three LEDs indicating the times that signal is given and response is expected. The response box also had two buttons allowing the subject to state his/her choice.

The subject booth and the control room can be seen in Figure 3.1 below:

Figure 3.1 – The subject booth (left) and the control room (right). The subject can be seen from the control room.

3.3 Stimuli

The stimulus was applied on the terminal phalanx of the middle finger. The length of the phalanx was measured before the experiment (the distance between the joint line and fingernail). The contact point was normalized as: (phalanx length)*1.5/3.5 cm from the joint line; and marked on the subject's finger with a felt-tip pen. This location approximates the center of the finger pad. The stimulus contactor probe was applied to this point.

The contactor size is an important factor that affects the thresholds, especially at the high frequencies while P channel is effective. The P channel is known to be capable of spatial summation. Thus, for the activation of the P channel, a large contactor area was used. Bolanowski showed that no thresholds can be measured at any frequencies with a contactor area of 0.008cm^2 for the P channel, but with 2.9 cm^2 contactor area, thresholds can be measured between 35-500 Hz for this channel [24]. Therefore, the stimulus was applied using a cylindrical contactor with 0.126 cm^2 surface area (The size of the contactor in the study of Güçlü and Bolanowski was taken as reference [28]. The contactor did not have a surround since a surround introduces an additional edge on the skin, which makes the interpretation of the results more difficult.

The test stimulus was a burst of sine wave. The burst started and ended as cosine-squared ramps with 50 ms rise and fall times. The duration between the half power points of the bursts was 500 ms. The stimulus was presented in one of the two time intervals, indicated by lights of different colors. (See Figure 3.2)

The masking stimulus was also a burst of sine wave, but with duration of 1 sec. Rise and fall times of masking stimulus were also 50 ms. The duration between the beginnings of two masking stimuli was 2 sec. The test stimulus was presented 150 ms after the masking stimulus. In the forward-masking experiments, masking stimulus was presented in both time intervals, but test stimulus was presented only in one of the two intervals. (See Figure 3.3)

The thresholds (displacements) were expressed in decibels referenced to 1μm peak displacement.

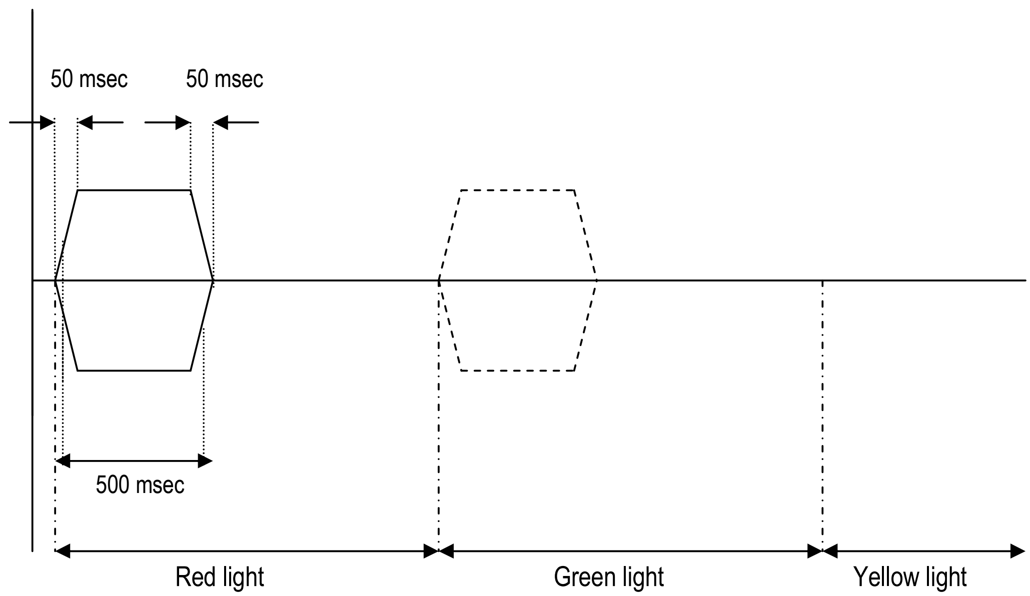

Figure 3.2 – Stimulus diagram for absolute threshold measurement by two-interval forced choice paradigm. The stimulus will appear in one of the two intervals indicated by red and green lights.

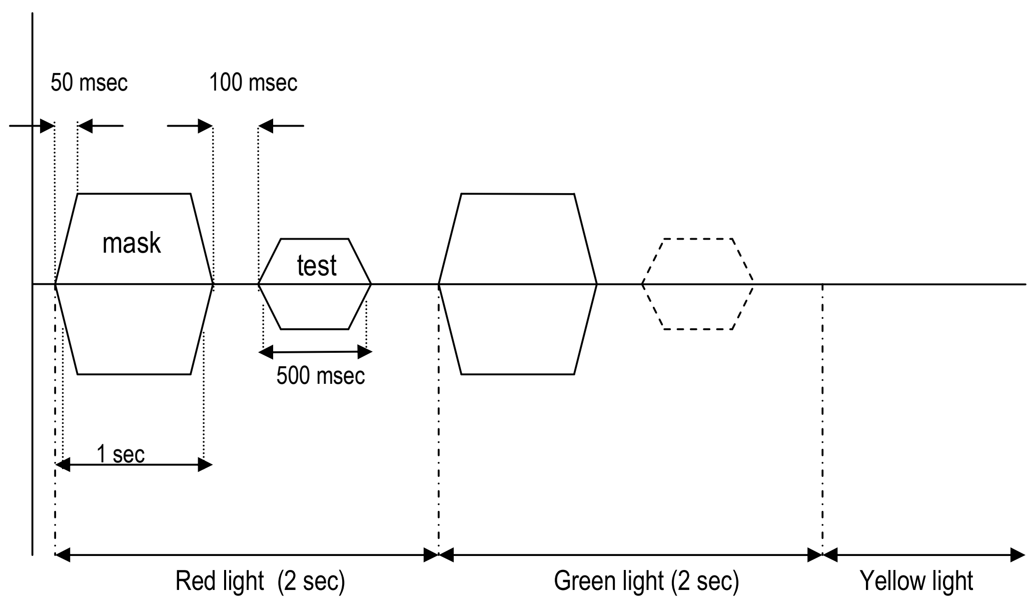

Figure 3.3 – Stimulus diagram for masked threshold measurement by two-interval forced choice paradigm. The test stimulus will appear in one of the two intervals indicated by red and green lights. Masking stimuli are presented in both intervals.

3.4 Experiments

In this study, the tactile thresholds of the children were compared to adults. For this purpose, first, the absolute tactile thresholds of subjects were obtained at different frequencies. Then, the tactile thresholds of NP I channel were measured. P channel was masked by a forward-masking procedure in order to measure the NP I channel thresholds, since P channel and NP I channel have similar vibrotactile thresholds at the measurement frequency, 40 Hz. The appropriate masking level of this procedure was found from masking functions of the subjects. Thus, before measuring NP I channel thresholds, masking functions were obtained.

To ensure continuous contact with the skin during stimulation, a constant static indention of the contactor was applied. In early works, it had been shown that the thresholds are affected by static indentation [29]. Therefore, the displacements were produced about a fixed static indentation of 0.5mm (The study of Güçlü and Bolanowski was taken as reference [28]). The initial contact was determined by measuring the resistance between the apparatus and the subject's skin. The resistance decreases evidently when the contactor surface touches the skin. The static indentation was adjusted by a micrometer after the initial contact and was monitored during the experiment by a camera. The subject's finger was fixed in modeling clay to prevent any motion.

It had been shown by Bolanowski and Verillo (1982) that variation in skin surface temperature can significantly affect vibratory sensitivity, especially for higher stimulus frequencies [30]. For P and NPII channels, which are more efficient at high frequencies, the temperature sensitivity is high, where NPI and NPIII channels, effective at low frequencies, have slight temperature sensitivities. Because the sensitivities of some channels are affected, the temperature was measured and recorded. The temperature was not controlled but its variation did not exceed 5°C.

3.4.1 Measuring the Absolute Thresholds

Thresholds obtained as a function of frequency in earlier works have three regions [24]. There is a flat region between 0.4 and 3.0Hz, which is relatively frequency insensitive. Second region is a frequency dependent, linear region which has a slope of 5.0db/octave, and which lies between 3 and 40Hz. The third region is the high frequency region between 40-600Hz, and it has a U-shape. This region depends on frequency with a higher slope than the second region between 40-100Hz.

Considering the shape of threshold-frequency characteristics obtained in earlier studies, six measurements were done at a frequency range of 2-500Hz (2Hz, 10Hz, 40Hz, 100Hz, 250Hz, and 500Hz) to obtain the threshold-frequency characteristics. Therefore, six sessions of absolute threshold measurements were needed for each subject. At each session, the subject was presented with the same test condition four times, and the average of these data was used to constuct the threshold-frequency characteristics.

3.4.2 Forward Masking Method

It is known that vibrotactile threshold at a certain frequency is elevated when an adequate masking stimulus is presented before the test stimulus; and this elevation increases when the masking level is increased.

To obtain the masking level-threshold shift function for each subject, a 250 Hz masking stimulus was presented before the 250 Hz test stimulus. Thresholds were measured for four masking levels for each subject. Thus, four sessions were needed to obtain the masking functions. At each session, the subject was presented with the same test condition four times, and the average of these data was used to form the masking functions.

The NPI channel thresholds were also measured using the forward masking method, because the P channel should be elevated to isolate and measure the NPI channel threshold at 40 Hz. An adequate masking level was chosen from the masking functions for each subject. Then, this masking stimulus at 250 Hz was presented before the 40 Hz test stimulus. By this method, the P channel was elevated, as in masking functions, and the threshold measured at 40 Hz is NPI channel threshold.

3.4.3 Two-Interval Forced-Choice Paradigm

The thresholds were measured by a two-interval forced-choice paradigm. This procedure ensures that the results were independent of the subject's criterion. The stimulus was presented at random in one of two intervals of equal duration. The intervals were indicated to the subject through presentation of two lights, the first by red light and the second by a green one.

The probability of the signal appearing in one or the other interval was 50%. The subject responded, when a yellow light is presented after the two intervals, by choosing the interval that he/she believed that contained the stimulus and by pressing the corresponding button. The yellow light blinked to signal a correct response to the subject.

The stimulus intensity was decreased by a 1dB step after every three correct responses, not necessarily consecutive. Every time an incorrect response occured, the stimulus intensity was increased by a 1dB step. In this way, the threshold was tracked at 75%-correct detection probability [31]. The experiment was stopped when the stimulus intensity changes within ±1dB range about an intensity level for the last 20 trials. This level was recorded as threshold.

3.5 Analysis

Each measurement was repeated 4 times on every subject. The graphs to be presented are the averages of these data. Error bars shown in the figures signify the standard errors of the mean.

In order to test if there is a significant difference between adults and children, statistical tools are necessary. Two-sample t-test, in Microsoft® Excel 2002, was used for this purpose.

Hypothesis testing methodology is such that the rejection of the null hypothesis is based on evidence from the sample that the alternative hypothesis is far more likely to be true. Microsoft® Excel calculates a P value for the t-test. P value is the probability of obtaining a test statistic equal to or more extreme than the result obtained form the sample data, given that the null hypothesis is true. If P is greater than the significance level, the null hypothesis can not be rejected. Significance level is set $\alpha=0.05$ for all t-tests in this study. (*Level of significance of the statistical test*: The probability of committing a Type I error, denoted by α. A Type I error occurs if null hypothesis is rejected when in fact it is true and should not be rejected.)

4. RESULTS

4.1 Absolute Thresholds of Children

Figure 4.1 shows the vibrotactile thresholds of children as a function of frequency. The threshold values were obtained by averaging the absolute thresholds of 9 children at each frequency: 2, 10, 40, 100, 250, and 500 Hz. The stimulus is a sinusoidal burst, delivered through a cylindrical contactor with a surface area of 0.126 cm^2, and no surround around it. The threshold values are decibels referenced to 1 micrometer and the error bars represent the standard error of the mean.

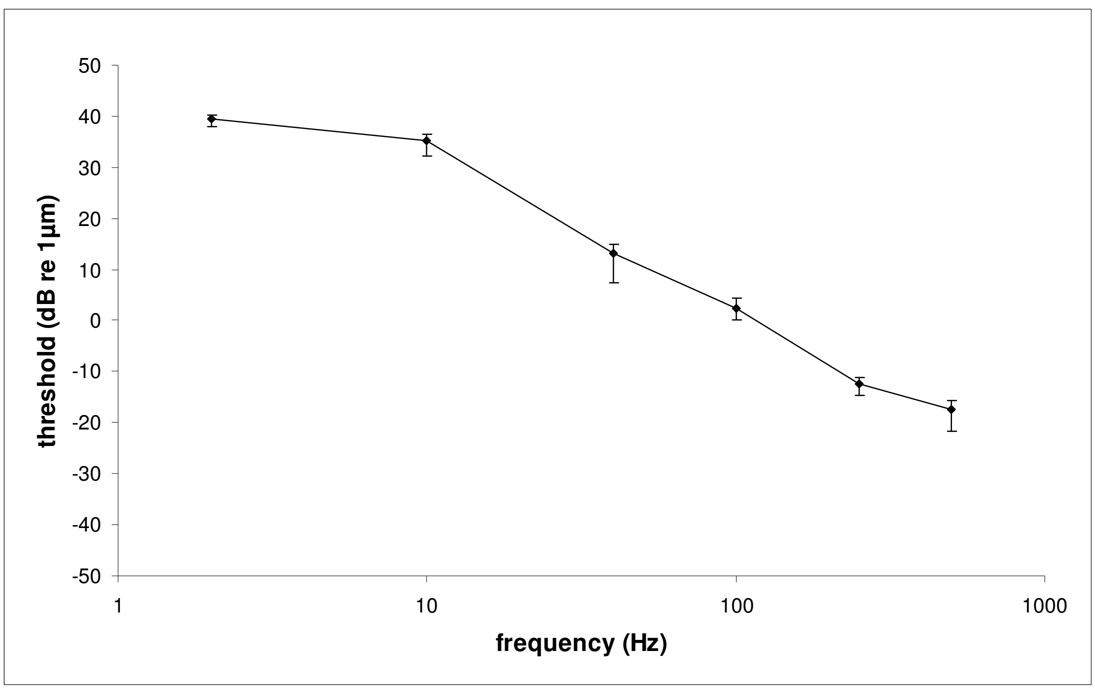

Figure 4.1– Absolute vibrotactile thresholds of children as a function of frequency. The error bars represent the standard error of the mean.

The general form of the curve mimics the previously reported threshold-frequency characteristics obtained in similar conditions [24]. It seems that the curve has two separate segments. In the low frequency region, extending up to ~10 Hz, the threshold is very slowly decreasing as the frequency increases. In the high frequency region, from ~10 Hz to 500 Hz, the curve has a higher slope, but again the threshold decreases with increasing frequency. In previous studies on adults, the high-frequency region has a U-shape, as seen in Figure 4.2. However, curve from children does not have this shape. The children may have the lowest threshold at higher frequencies than adults in previous studies. However, the U-shape can be seen in the individual threshold-frequency characteristics of some children (See Figure 4.3) [24].

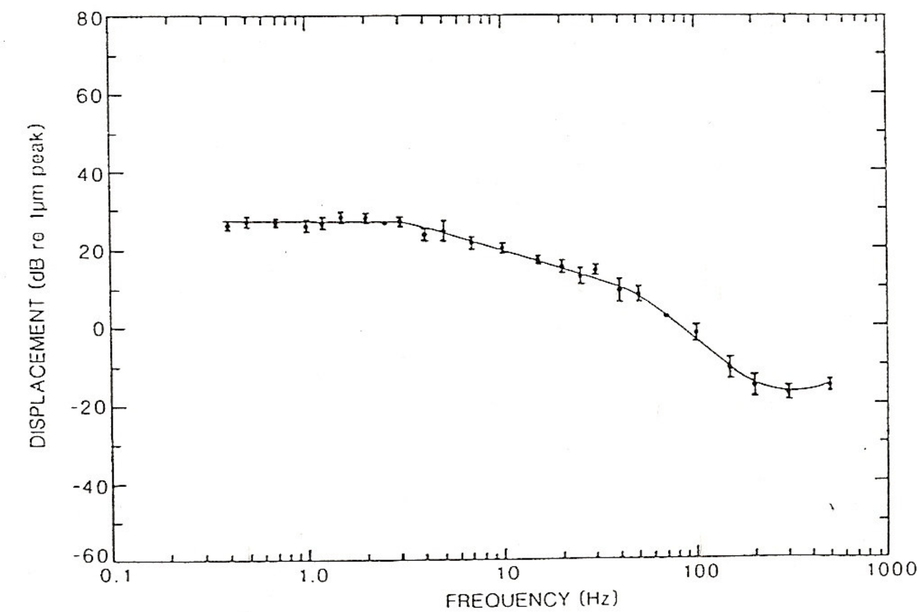

Figure 4.2 – Threshold-frequency characteristics of adults [24]. The data points are the averages of five observers. Error bars signify the standard error of the means. Contactor size is 2.9 cm^2.

Given that the curve in Figure 4.1 has two distinct parts, it can be suggested that different channels are active in these two parts. In previous studies, the low-frequency part is assumed to be produced by the NPI channel, while the high-frequency part is produced by the P channel. In the following sections, thresholds are shifted using masking stimulus and the two separate channels are shown clearly.

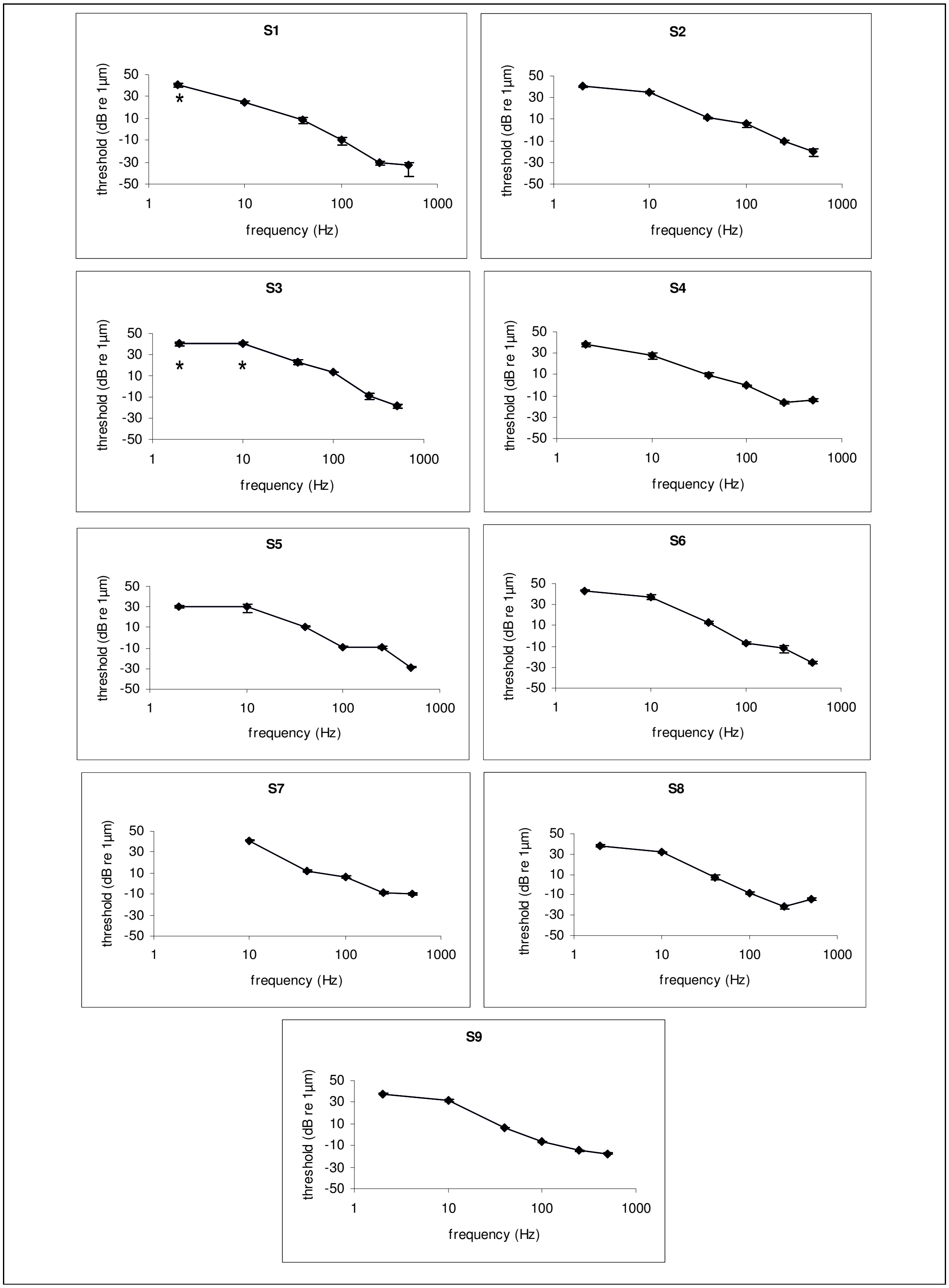

Figure 4.3 – Threshold-frequency characteristics of children are given individually. Thresholds are in dB re 1 micrometer. Error bars are standard error of the means. For all subjects, the thresholds at each frequency are the averages of 4 distinct measurements. (*) sign indicates that the data point it is the average of less than 4 measurements. Details are given in Table 4.1.

As mentioned in Methods, the threshold value of a subject at a certain frequency was calculated as the average value of four distinct measurements at that frequency. However, in some cases, decoupling could occur between skin and probe if the amplitude is high [32]. The decoupling region for amplitude of vibration is given in Figure 4.4. The threshold values which may be in decoupling region were not taken into account for the analyses. These cases are given in Table 4.1.

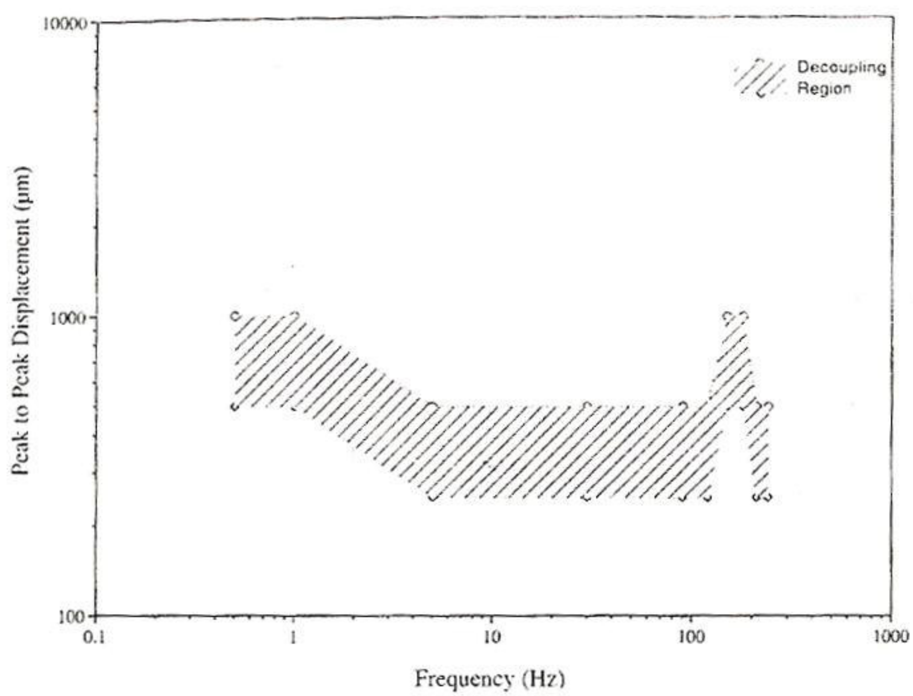

Figure 4.4 – The peak-to-peak displacements required to produce decoupling between the stimulus probe and the skin as a function of frequency [32].

Subject:	Frequency at which decoupling occurs:	Omitted measurements:
S1	2 Hz	1 measurement was omitted
S3	2 Hz	1 measurement was omitted
S3	10 Hz	2 measurements were omitted
S7	2 Hz	4 (all) measurements were omitted

Table 4.1– These thresholds may be in the decoupling region; therefore they were not taken into account for calculating the averages.

4.2 Comparison with Adults

In order to compare the tactile thresholds of children with adults, the data, obtained from adults at 40 Hz and 250 Hz were used [28, 33]. Since there were 9 children, the comparison was made with a group of 9 adults, whose ages ranged between 21 and 27.

Table 4.2 gives the absolute threshold values of children and adults at 40 Hz and 250 Hz. The comparison of the average values of children and average values of adults is given in Figure 4.5. Again, the error bars show the standard error of the means.

ADULTS			**CHILDREN**		
	250 Hz thresholds (dB)	40 Hz thresholds (dB)		250 Hz thresholds (dB)	40 Hz thresholds (dB)
A1	-15	0.2	S1	-30.8	9.1
A2	-2.3	14.4	S2	-10.4	10.7
A3	-9	13.0	S3	-8.3	23.2
A4	-16	12.1	S4	-16.2	9.8
A5	-14.8	11.3	S5	-8.8	11.0
A6	-13.6	8.3	S6	-11.2	12.8
A7	-11.6	16.8	S7	-8.5	12.3
A8	-12	14.7	S8	-21.6	7.6
A9	-26	14.6	S9	-14.7	6.3
AVG	-11.4	12.7	AVG	-12.4	13.0

Table 4.2 – Absolute tactile thresholds of adults and children at 250 Hz and 40 Hz. The values are in decibels referenced to 1 micrometer.

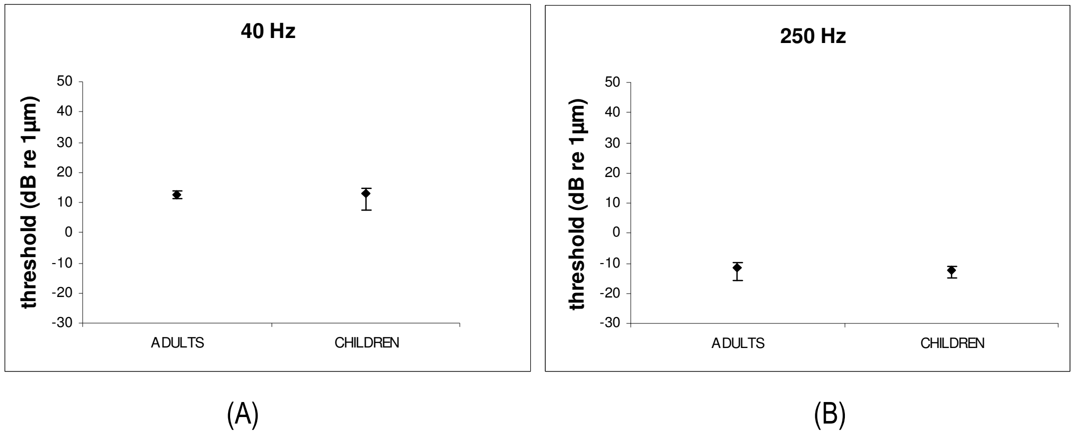

Figure 4.5 – Average values of tactile thresholds of adults and children were compared. (A) Threshold values at 40 Hz, (B) Threshold values at 250 Hz. The error bars represent the standard error of the means.

In order to find if there is a significant difference between the thresholds of adults and children, two-sample t-tests were used. The null hypothesis was that the thresholds of children and adults come from the same population. T-tests were run for 40 Hz and 250 Hz thresholds separately. Test results are below:

40 Hz test: P=0.91
250 Hz test: P=0.72

Since P values of both tests are above 0.05, the null hypothesis can not be rejected in both tests. As a result, the threshold values of children and adults are not significantly different, contrary to my proposal.

4.3 Masking the P Channel

In this section, the vibrotactile thresholds of the NPI channel of children is analyzed at 40 Hz. The P channel must usually be masked to ensure the detection of 40 Hz stimulus by the NPI channel [28]. A forward masking procedure was used to elevate the thresholds of the P channel with respect to NPI channel. P channel is known to mediate the thresholds of high frequencies, so it can be masked using a 250 Hz stimulus presented prior to the 40 Hz test stimulus.

All subjects respond differently to different levels of masking stimuli, and the elevation of thresholds is different for each subject. Therefore, the masking functions of the subjects need to be found individually.

4.3.1 Masking Functions

In order to obtain the masking functions of the subjects, the P channel was masked by a 250 Hz stimulus, and the test stimulus frequency was also set to 250 Hz. Then, for four different amplitudes of the masking stimulus, the threshold at 250 Hz was measured. Then, the threshold shift was plotted as a function of the masking level (See Figure 4.6). Threshold shift is the amount of shift referenced to the 250 Hz threshold measured without masking for each subject. Masking level is expressed as sensation level, where sensation level is $SL = 20*\log (A_{masker}/A_{threshold})$. For each subject, the masked thresholds were calculated as the average of four measurements at each masking level.

A linear regression line was fit to each masking function (Figure 6). The R^2 values for linear fits are also shown on the graphs. These regression lines test whether the masking functions can be considered to be linear with respect to double logarithmic axes (i.e. power function). Six of the subjects have threshold shifts which almost linearly increase with the masking levels (S1, S2, S3, S4, S7, and S9). The other subjects have different characteristics than an increasing model. However, all subjects have elevated P channel thresholds because of masking.

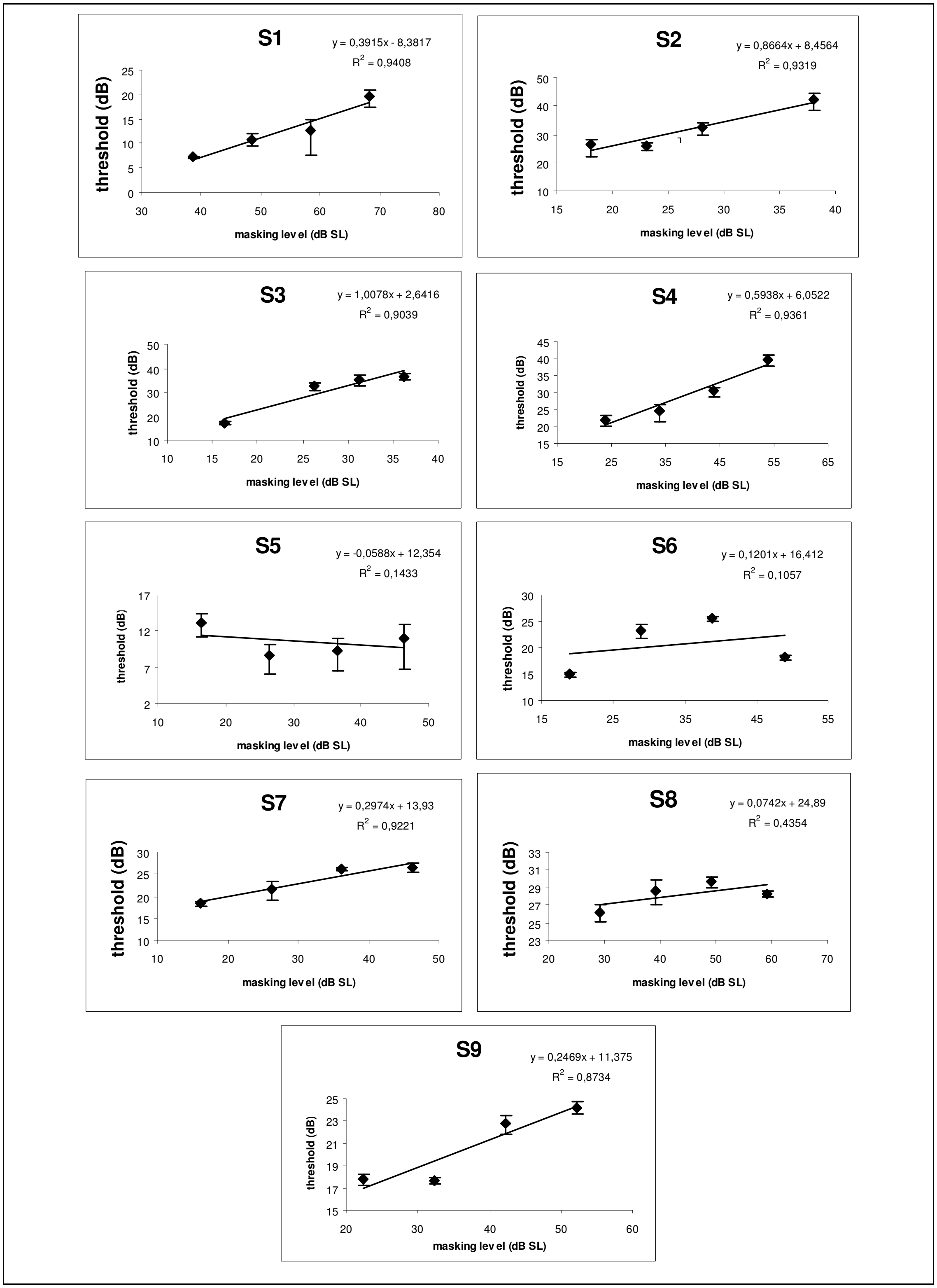

Figure 4.6– The masking functions of children. The curves represent the threshold shifts caused by a 250 Hz masking stimulus. Both the threshold shift and masking level are in decibels. Each data point is the average of four distinct measurements and error bars indicate standard error of the means.

4.3.2 Detection Mechanism

Since the masking functions for each subject are different, the masking levels and the masking effects obtained for each subject are different. For measuring the thresholds of the NPI channel at 40 Hz, different masking levels were applied to each subject. The masking level was chosen such that there is sufficient threshold elevation in P channel. Masking levels chosen for each subject are shown in Table 4.3.

Subject	S1	S2	S3	S4	S5	S6	S7	S8	S9
Masker Level	68.4	38.0	36.3	53.8	46.4	38.9	36.2	49.2	42.3

Table 4.3 – Masker levels used to elevate the thresholds of the P channel for each subject. Masking levels are dB sensation levels (Figure 4.6).

By using the masking levels shown in Table 4.3, the forward masking procedure was applied for 40 Hz test stimulus. Four different measurements were taken for each subject, and the averages were calculated. These masked values at 40 Hz were compared to unmasked absolute thresholds at 40 Hz. Table 4.4 shows the masked and unmasked values. These values were compared by using a two-sample t-test for each subject. The null hypothesis of all tests is that masked and unmasked thresholds at 40 Hz come from the same population for each subject. Calculated P values are also shown in Table 4.4. All P values are smaller than $\alpha=0.05$, so the null hypothesis is rejected for all of the subjects. As a result, the unmasked and masked thresholds for each subject are significantly different.

Subject	S1	S2	S3	S4	S5	S6	S7	S8	S9
Unmasked threshold (dB)	9.1	10.7	23.2	9.8	11.0	12.8	12.3	7.6	6.3
Masked threshold (dB)	19.1	37.7	39.2	29.9	17.8	31.2	19.6	24	18.5
P value	0.016	<0.001	0.003	<0.001	<0.001	<0.001	0.003	<0.001	<0.001

Table 4.4 – Unmasked and masked thresholds for each subject in decibel referenced to 1 micrometer. P values are the results of t-tests done for comparison of each unmasked-masked threshold couple in the table.

At 40 Hz, the P and NPI channels have similar thresholds. Since all tactile channels are assumed to be independent, at least peripherally, interactions of the remaining two channels need not be considered at threshold level [28]. There are two possible scenarios for the detection of stimulus at 40 Hz (See Figure 4.7).

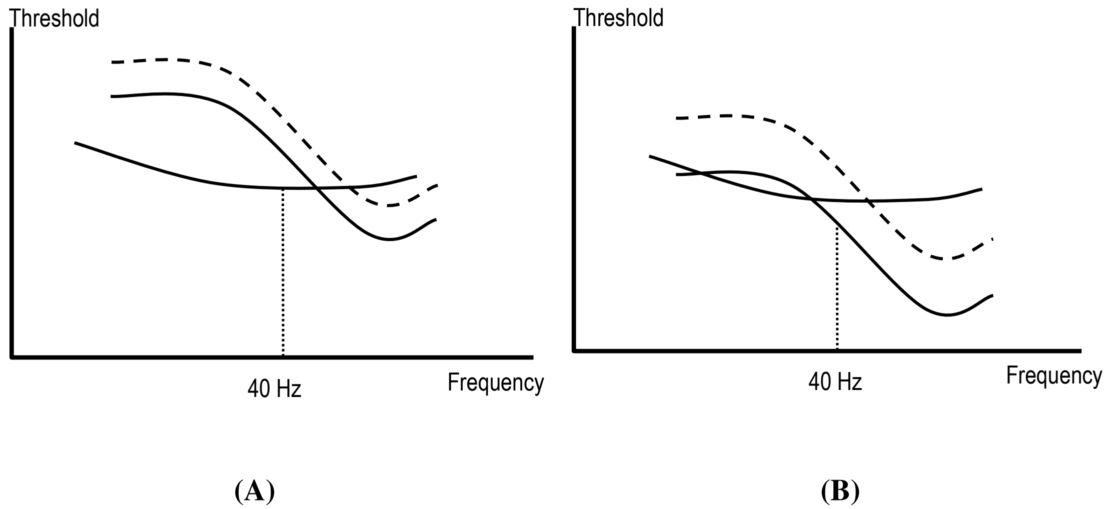

Figure 4.7 – Two possible scenarios regarding the detection of a 40 Hz stimulus by using model sensitivity curves as a function of stimulus frequency. (A) Threshold of the NP I channel is lower than threshold of the P channel; test stimulus is detected by NP I channel. Masking the P channel has no effect on detection of 40 Hz stimulus. (B) Threshold of the P channel is lower than threshold of the NP I channel, so the detection is mediated by P channel. However, if P channel is masked (dashed line), test stimulus is detected by NP I channel.

In figure 4.7A, the unmasked detection at 40 Hz is mediated by NP I channel. In this scenario, masking the P channel would have no effect on the thresholds measured at 40 Hz. However, in Figure 4.7B, the unmasked detection at 40 Hz is mediated by P channel. Therefore, masking P channel would affect the threshold.

Since the masked and unmasked thresholds are statistically different at 40 Hz, and since it can be seen that the thresholds are elevated by masking procedure, we can conclude that the first scenario is not valid. Yet, in the second scenario, there is another possibility. P channel may be elevated, but not enough to exceed the NPI channel (See Figure 4.8). In this case, the threshold shifts of 40 Hz and 250 Hz at selected masking level should be equal. That is, if we add threshold shifts of the P channel calculated from the masking functions at 250 Hz to the unmasked threshold at 40 Hz, we should obtain the masked threshold of P channel at 40 Hz.

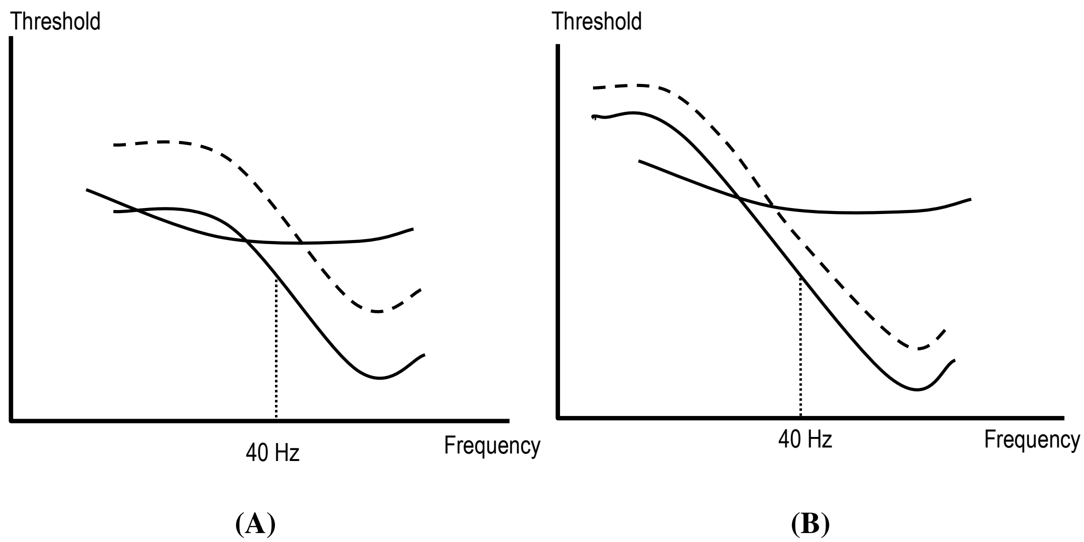

Figure 4.8 – (A) P channel is masked and elevated enough so that the detection is mediated by NP I channel. (B) P channel is masked and elevated, but it does not exceed the threshold of NP I channel, so the test stimulus is still detected by P channel.

The masked thresholds of P channel at 40 Hz were calculated by adding 250 Hz threshold shifts to unmasked thresholds at 40 Hz, and compared to the masked thresholds at 40 Hz found in the experiments, using two sample t-tests for each subject. Test results are shown below:

Subject:	S1	S2	S3	S4	S5	S6	S7	S8	S9
P value:	0.037	0.002	0.002	<0.001	0.011	0.003	<0.001	0.002	<0.001

It is obvious that masked threshold of P channel is higher than masked thresholds at 40 Hz, therefore, masked thresholds are mediated by NP I channel.

Figure 4.9 illustrates the unmasked and masked thresholds at 40 Hz and the calculated masked thresholds of P channel at 40 Hz for each subject.

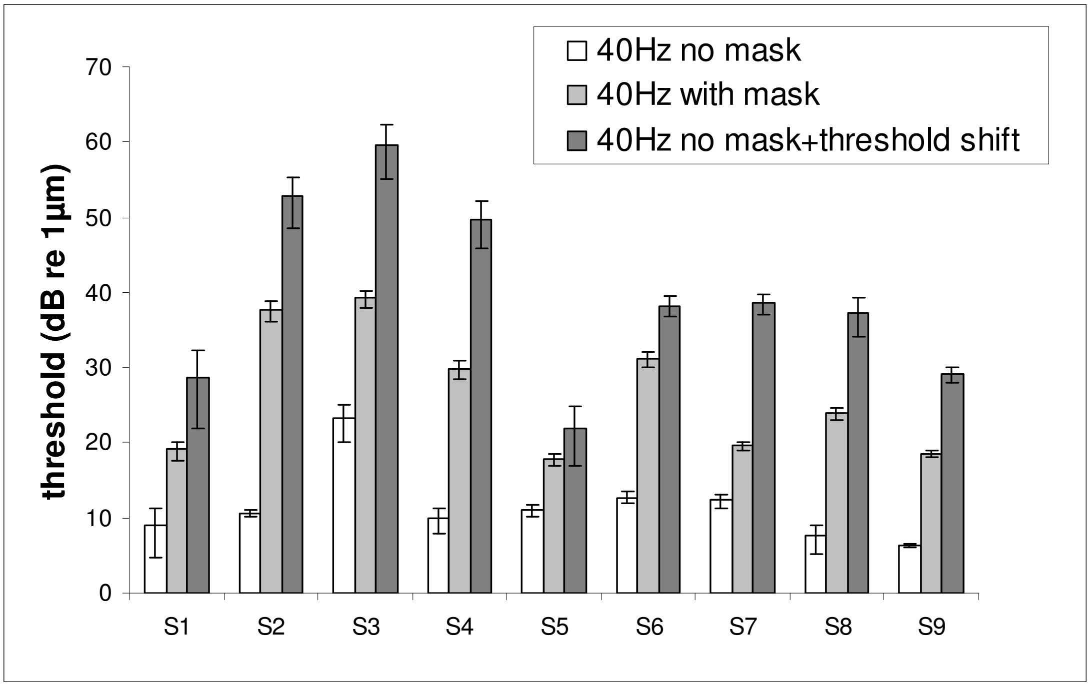

Figure 4.9 – White bars are the 40 Hz absolute thresholds of the subjects. Light gray bars are the masked thresholds at 40 Hz. Dark gray bars are the theoretical masked thresholds of P channel at 40 Hz. Dark gray bars were calculated by adding the threshold shifts at 250 Hz to unmasked 40 Hz thresholds. Every bar represents the average value of four distinct measurements, and error bars represent the standard error of the means.

4.4 Comparison of the NPI channel thresholds of children and adults

In this section, the NPI channel thresholds of children were compared to the NPI channel thresholds of adults, which were obtained from previous studies [28, 33].

The masked thresholds for adults and children can be seen in Table 4.5, in decibels referenced to 1 micrometer. The average thresholds are plotted in Figure 4.10.

ADULTS		CHILDREN	
A1	19.0	S1	19.1
A2	21.6	S2	37.7
A3	18.7	S3	39.2
A4	20.8	S4	29.9
A5	20.6	S5	17.8
A6	17.7	S6	31.2
A7	20.8	S7	19.6
A8	20.4	S8	24.0
A9	18.4	S9	18.5
AVG	19.9	AVG	30.0

Table 4.5 – Masked thresholds at 40 Hz for children and adults. The values are the averages of four measurements and are expressed in decibels referenced to 1 micrometer.

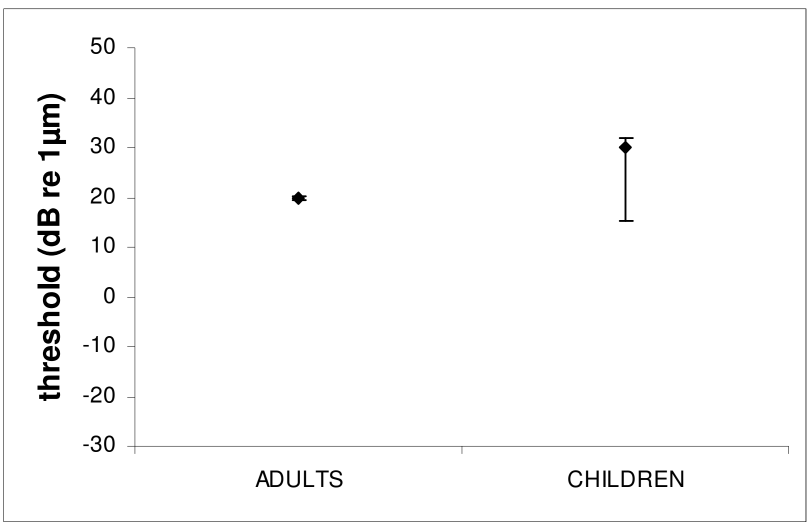

Figure 4.10 – The average NP I channel thresholds for children and adults. Both groups contain 9 subjects. The thresholds are given in decibels referenced to 1 micrometer. Error bars represent the standard deviations.

Two-sample t-test was applied to the data. The null hypothesis is that the children and adults have thresholds from the same population. P value was calculated to be 0.049, very slightly less than $\alpha=0.05$. The null hypothesis may be rejected. Therefore, adults and children may have different NPI thresholds at 40 Hz. However, more data are needed to reach a firm conclusion.

5. DISCUSSION

The aim of this study was to measure the vibrotactile thresholds of children and to compare these measurements with adults' vibrotactile thresholds.

It can be seen that the general form of the threshold-frequency characteristics mimics the previously reported threshold-frequency characteristics. However, the threshold values are found to be different from the previous studies, because different methods were used in the experiments in most of the other studies. For example, in the study of Bolanowski et al. (1988), the experiments were done by using a contactor with surround, and the contactor size was chosen to be 2.9 cm^2 [24]. It is known that P channel, sensitive at high frequencies, is highly affected from the contactor area. Most importantly, the thresholds were measured at thenar eminence in that study, while in my study, fingertip was used. Considering these differences, it is not unexpected that thresholds found in my experiments are higher than the thresholds found in Bolanowski's study. Since similar methods were used in most of the previous studies, the thresholds were not compared to them. The methods I have used are exactly the same that Güçlü and Bolanowski used in [28], and Kalkancı used in [33]. Thus, the comparison was made with these measurements.

The children's and adults' threshold values were compared at 40 Hz and 250 Hz; and no statistical difference was found at both frequencies. When the previous studies are considered, it can be seen that there is not much alteration in thresholds between the ages 10 and 30 [2-5]. These studies show that tactile sensitivity decreases with age; but the decrease is mostly after age of 60. In my study, the comparison is made between two groups of ages 8-11 and 21-27, thus, it is predictable that thresholds are not different. Moreover, the measurements were made on thenar eminence in previous studies. As stated in Stuart's article [5], fingertips are more sensitive and more specialized in touch than most of the body. So, the decrease of sensitivity by aging may be slower at fingertips than other body regions that measurements were done.

Loss of tactile sensitivity with aging is that the thresholds are elevated in older subjects as a result of reduction in the density of tactile receptors that occurs with aging. In addition to reduction in density, receptors undergo morphological changes with aging, which is also a reason for loss of sensitivity. Since thresholds of adults [28] are not different than children's thresholds in my study, we can say that morphological changes and reduction in receptor density happen in much older ages.

The threshold-frequency characteristics, found by Bolanowski et al. (1988) were given in Results, Figure 4.2. Comparing the thresholds in my study with this curve, at lower frequencies, the threshold difference is greater than at higher frequencies. For 2 and 10 Hz, the difference is over 10 dB; for 40, 100 and 250 Hz, the difference is between 5 and 10 dB; and for 500 Hz, it is nearly 2 dB. Here, the most important differences between the experiment conditions are the stimulus location, the contactor size and the contactor surround. Low frequencies are known to be mediated by SAI (0.4-2 Hz) and FAI (2-40 Hz) fibers where high frequencies are known to be mediated by FAII (40-500 Hz) and SAII (100-500 Hz) fibers. When the results are compared, it can be said that type I fibers are more affected from the differences than type II fibers. Thus, receptive field size and innervation density properties of the fibers may be responsible for the differences. Also, the contactor surround has a confounding effect on the threshold values.

Gescheider et al., 2002, showed that, for 0.1 cm^2 contactor size, fingertip threshold was 7-8 dB lower than thenar eminence threshold at 300 Hz; and the difference decreases as contactor size increases [34]. According to this study, the reason is that for P channel the probability of exciting the most sensitive units requiring the lowest levels of stimulus intensity increases as the contactor size increases. Although it is accepted that NP channels do not have spatial summation property, "the probability of exciting the most sensitive units" case *may* also be valid for these channels.

Using the forward masking method in the experiments, the P channel was masked, and NP I channel thresholds were measured. The method was successful, and the P channel was elevated. With an adequate amount of elevation applied to the P channel, the NP I channel thresholds were measured and it is shown that two different channels were active before and after the masking. By this method, not only the children and adults' NP I channel thresholds were compared, but also it was shown that four-channel theory can be used to understand the perception mechanism at 40 Hz.

Gescheider et al., 1994, has also measured the NPI channel thresholds with another method [2]. They isolated the NPI channel from the P channel by using a very small size contactor (0.008 cm^2). Result is that, the adults' and children's thresholds were nearly same at 40 Hz (~15dB). These thresholds are a little lower than Güçlü and Bolanowski's study [28] (~18-21 dB) and my study (~17-39 dB). Again, the contactor size and location may be the reason.

6. FUTURE WORK

This study can be used as a reference in future studies of tactile perception. For example, the data obtained from the children may be compared to older people, especially over 60, or higher levels of processing can be investigated by using EEG. Also, it is known that autism has an effect on sense of touch. Some autistic children are disturbed by touch while some of them want to be touched and held. This study may be a reference for investigating the tactile properties of autistic children and comparing the results with normal children.

There are many modeling studies about tactile sensitivity. This experimental study may be a reference for these modeling studies. The behavior of skin and mechanoreceptors depending on age may be investigated and used in modeling.

The psychophysical studies about touch and skin can be combined with physiological and technological researches and developments, and used in robotics to imitate the sense of touch. Imitating the sense of touch will be a great improvement for prosthetics.

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