THERMAL EFFECTS UPON HUMAN VIBRATORY SENSITIVITY

by

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INTRODUCTION

Thermal changes have long been known to affect mechanoreception in man. A classic example is Weber's deception: two warm coins placed on the forehead are perceived to be of the same weight as a single cold coin. Temperature has been shown to be a factor in punctate pressure sensitivity, localization error, and two-point threshold; these findings will be discussed later. The present study will attempt to expand on the recent literature regarding another mechanoreceptive modality: vibratory sensitivity. The effects of heating and cooling the skin on both high and low frequency vibrotactile thresholds will be studied in order to add to the varied, yet limited research heretofore reported in the area.

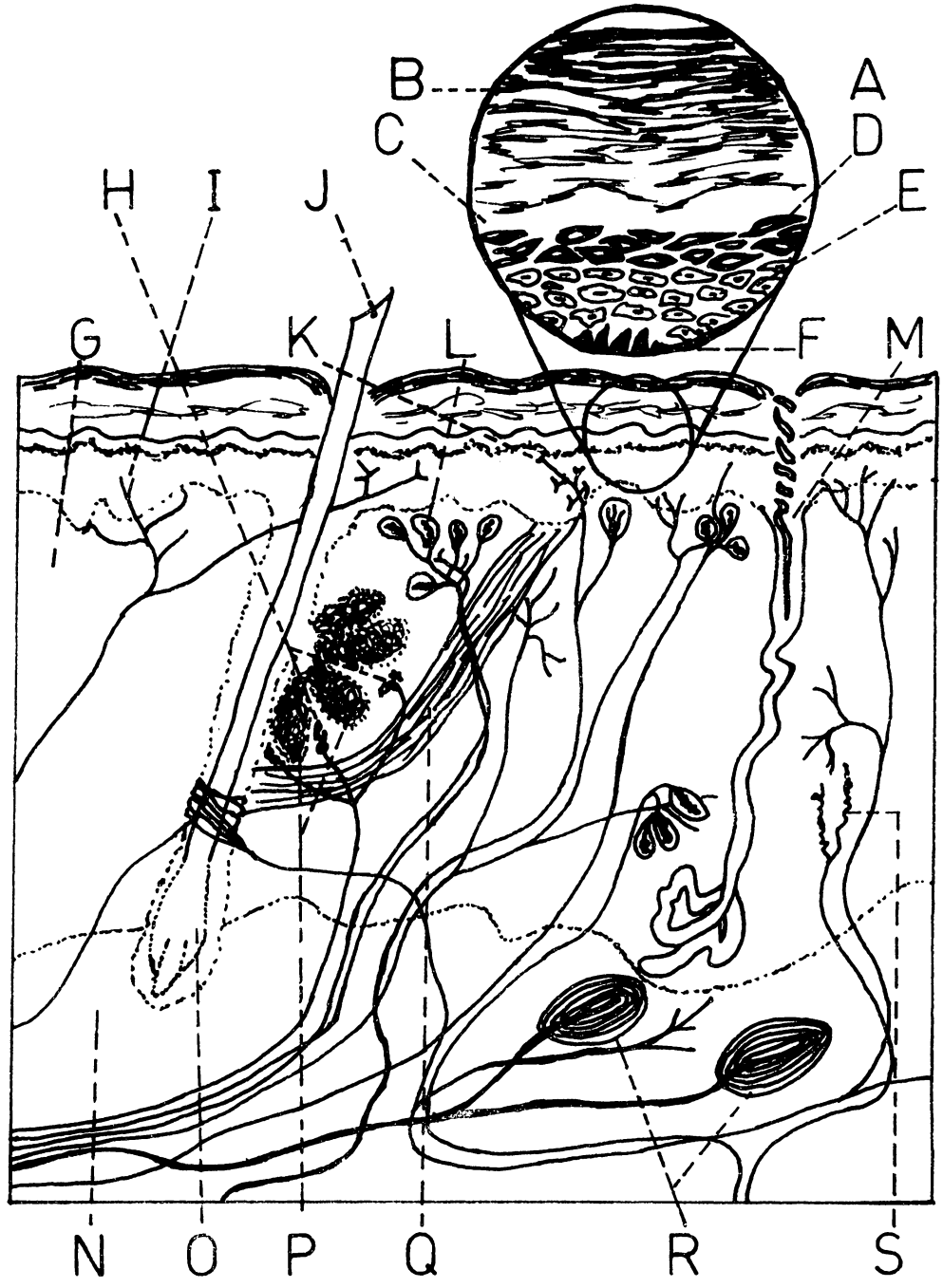
Of all the sensory systems existing in man, the skin or integument is the first to develop. The largest sensory system, the integument envelopes the body and also stretches inside- into the nasal, oral, aural, and other cavities. In a manner of speaking, cutaneous tissue provides man and beast devices with which he can receive communication continuously from his environment and from other organisms. And yet, as Geldard (1972) pointed out, the intricacies and even the simplicities of the skin are far from understood. In fact, the skin as a sensory system is probably the least understood with regard to the anatomical functions of the receptors

within.

There are four main types of cutaneous tissue, two of which will be of import in this study: hairy and glabrous skin. The former is characterized by hair fibers and comprises the majority of the body surface in most mammalian species. Glabrous skin is found on body surfaces lacking hair, such as the palms of the hands and the soles of the feet. The types of nerve endings found in hairy and glabrous skin have been listed by Verrillo (1968). Four types of endings are characteristic of glabrous skin: the dermal nerve network (or free nerve endings) and its terminations, Meissner corpuscles, Pacinian corpuscles, and Merkel disks (herediform endings). In hairy skin both the dermal nerve net and the Pacinian corpuscle are found, along with basket nerve endings surrounding a lower portion of each hair follicle. Figure 1 shows the locations of these receptors in a hypothetical cross-section of cutaneous tissue- hypothetical in the sense that not all of these nerve endings are characteristic of any one of the four types of cutaneous tissue.

The most highly studied of the mechanoreceptors is the Pacinian corpuscle. This encapsulated ending was first isolated in 1741 by Lehman and was later described in 1835 by Pacini as being innervated by a single myelinated fiber. Cauna (1965) provided a detailed description of the whereabouts and the anatomy of the corpuscle. The Pacinian cor-

Figure 1. Cross section of the skin showing: A) enlargement of the epidermis and its layers, B) stratum corneum, C) stratum lucidum, D) stratum granulosum, E) stratum germinativum, F) basal cells; G) dermis; H) end bulbs of Krause; I) dermal nerve net; J) hair follicle; K) Merkel disks; L) Meissner's corpuscles; M) duct of sweat gland; N) connective tissue; O) basket nerve ending; P) sebaceous gland; Q) smooth muscle; R) Pacinian corpuscles; and S) Ruffini endings. After Bremer and Weatherford (1944) and Woollard, Weddell, and Harpman (1940).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puscle is widely distributed in cutaneous tissue, appearing heavily in such regions as the fingertips, palms, soles of the feet, and the viscera. The terminal end of its large, myelinated axon is surrounded by concentric layers of connective tissue (lamellae). Interlamellar fluid fills in the small spaces between these layers. If one were to cut a cross section of a Pacinian body, one would see a remarkable resemblance to a similar section of an onion (see Fig. 2a).

What is the function of such a structure? Lowenstein and Shalak (1966) have proposed a theory to explain how these structures interact to produce a mechanical sensation. According to Lowenstein and Shalak, the lamellae and their interconnections provide the elastic components of the system, while the interlamellar fluid provides the viscous element. The concentric rings pick up a vibration (or a displacement in the epidermis) and conduct this displacement from one layer to the next innermost layer. The vibration is dampened somewhat by each successive layer of fluid. This system provides a very adequate filtering device, for only vibrations of frequencies over 80 Hz provide enough initial displacement to stimulate the nerve ending in the core of the receptor; only a fraction of the outer surface pressure reaches the center (see Fig. 2b). Lowenstein and Shalak provided a useful analogy: Imagine an inflated balloon inside a larger inflated balloon. A slight dis-

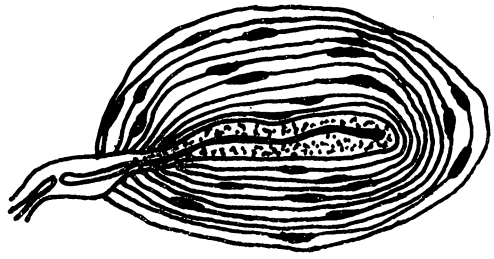
placement of the outer ballon's surface raises the inner pressure, but does not appreciably displace the surface of the innermost balloon. On the other hand, the amount of skin displacement necessary to produce a reliable response in a single corpuscle is minute- only 1/2,000 mm in 1/10 msec!

The dermal nerve net is characterized by several small, unmyelinated branches located near or within the lower layers of the epidermis. A highly diagrammatic view is presented in Figure 2c. Note that the number of endings in a single fiber can vary, so that the number of endings in a single fiber which are stimulated may vary, as well. The skin itself is an implicit part of this receptor mechanism, for as the skin surface is displaced, the endings are likewise displaced producing a burst of neural impulses. This burst of impulses is proportional to the degree of skin displacement, and the number of individual endings stimulated by that displacement. Therefore, precise localization of a punctate stimulus is afforded due to this spatial arrangement of fibers.

Four types of fibers sensitive to mechanical stimuli were isolated in the skin of the frog (Catton, 1962). Of these four types- A, B, C, and D fibers- only C fibers were found to be sensitive to vibratory stimuli. They were small, unmyelinated fibers which were stimulated by frequencies of up to 200 Hz.

There is a good deal of evidence showing that the C fibers in cutaneous tissue respond to both mechanical and

Figure 2. Structure of the Pacinian corpuscle and functions of the dermal nerve net and the Pacinian corpuscle. A) Cross section of a typical Pacinian receptor. After Ludel (1978). B) Highly schematic drawing of the probable functional relationship of the Pacinian receptor mechanism showing lamellae (L), fluid resistance (FR), the interconnections (I), and a rigid plane (RP). After Lowenstein and Shalak (1966). C) Schematic drawing of three dermal nerve net fibers as a punctate stimulus is applied. After Lowenstein (1966).



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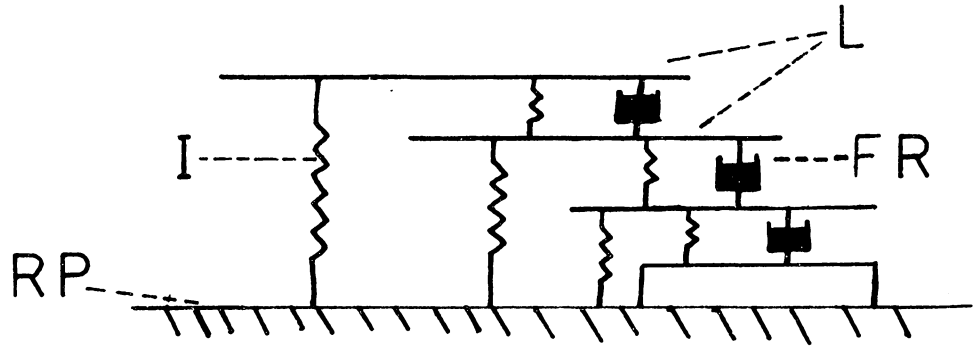

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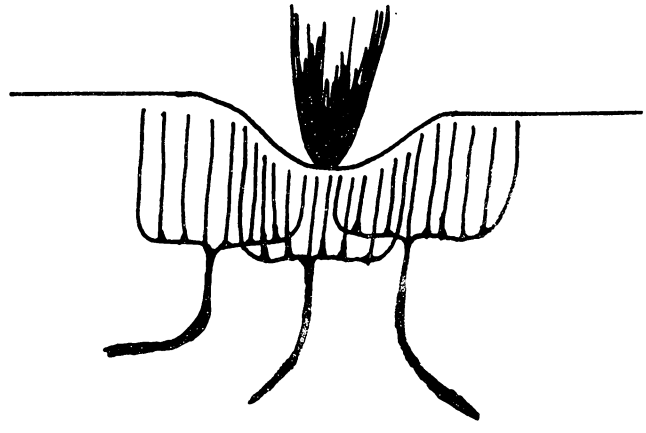


C.

thermal stimuli. Douglas and Ritchie (1962) found that most C fibers were indeed involved in both modalities. Maruhashi, Mizuguchi, and Tasaki (1952) found some C fibers responsive to thermal, some to mechanical changes, and some responsive to both. These findings were from electrophysiological preparations of the cat. Iggo (1960) recorded also from mammalian C fibers; responses to both mechanical and to thermal changes of greater than $\pm$ 10°C were evident. A dual mechanism has been observed in the glabrous skin of the palm and footpad of squirrel monkeys. These receptors responded both to temperature and to mechanical pressure (Burton, Forbes, and Benjamin, 1970). Keidel (1968) had stated that Pacinian corpuscles acted primarily as mechanoreceptors, but could function on a secondary basis as thermal receptors.

Recent work in vibratory sensitivity has identified a dual-receptor mechanism. This theory was elegantly stated and supported by Verrillo (1968) who identified two receptor systems contributing to vibratory sensation. One of these systems was sensitive to frequencies above 80 Hz and was responsible for both spatial and temporal energy summation of vibrations; the Pacinian corpuscles were singled out as the spatiotemporal summators. With regard to the other system, equivocal results have been reported. According to Verrillo, the other system lacked both the temporal and the spatial summation qualities. No receptors <u>per se</u> were singled out as the non-summators, and the dermal nerve net was ruled

out as the non-summating population due to the production of a flat threshold for the dorsal surface of the tongue (which contains free nerve endings but lacks Pacinian corpuscles). However, there are now data recorded from the tongue which show that the low-frequency receptor population may in fact aid in temporal summation (Telege, Fucci, and Blackmon, 1976).

Electrophysiological studies from non-human organisms have strongly supported the dual-receptor hypothesis. Sato (1961) recorded impulses from isolated Pacinian corpuscles resulting from sinusoidal vibration to the mesentery of the cat and found that these receptors responded maximally to frequencies of 150-200 Hz. From studies of the glabrous skin of the monkey (Talbot, Darian-Smith, Kornhuber, and Mountcastle, 1968; Lindblom and Lund, 1966), the dermal nerve net has been shown to be a source for the transmission of vibratory stimuli. This receptor network was shown to be tuned to the lower frequencies (under 80 Hz) and maximally sensitive between 30-40 Hz.

When thermal cutaneous stimuli are applied, the state of the vascular system must be taken into account (Geldard, 1972). If the blood vessels are dilated, heat transfer is greatly reduced- the vessels act as a sort of radiator, filtering the heat and cooling the underlying system. On the other hand, when cutaneous tissue is inflamed, cold sensations are reduced due to an exaggeration of the latency of their arousal. Therefore, depending on the vascular state of the

stimulated area, temperature transfer can be affected by as much as 0.5-1.0 mm/sec. The transfer of thermal change is a factor which greatly affects mechanoreceptive thresholds, as will become evident.

A number of studies have reported that thermal and mechanoreceptive sensations interact; that is, alterations in pressure thresholds occurred as a function of temperature. For the forearm and the hand, the site of tactile stimulation could be referred to more easily with subsequent stimulations of warmth than of cold. This localization error effect was more than likely generalizable to other stimulus sites as well (Green, 1978). However, Prestrude and Johnstone (1977) reported increases in both localization error and two-point threshold (the minimum distance at which two punctate stimuli could be reliably determined as two) with increases in temperature, and vice versa. Although the effect was smaller for localization error than for two-point threshold, this discrepancy was attributed to the motor aspects of the localization task as opposed to the pure sensory nature of two-point stimuli. However it has since been shown that a small stimulus produces a small interaction between the temperature and the touch systems (Stevens and Green, 1978), an issue which will be returned to later, which could account for the latter results.

The effects of skin temperature on punctate pressure sensitivity have also been considered. Minimum thresholds

for punctate sensitivity have been shown to be 35°C (Irving, 1963), and to be between 36-38°C (Allers and Halpern, in Weitz, 1941). Punctate pressure sensitivity to von Frey hairs remained relatively constant between 20°C and 40°C, decreasing sharply below 20°C, and decreasing insignificantly above 43°C (Stevens, Green, and Krimsley, 1977). This finding supported for the most part the report of Prestrude and Kash (1972). A triple-beam balance controlled by an eccentric crank was used to deliver punctate stimuli. For temperatures above 32°C, a decrement in sensitivity occurred (relatively proportional to the increment in temperature). Whereas their original procedure suggested a slight decrement in sensitivity also to temperatures below 25°C, a retest suggested a slight increase at these temperatures. Johnstone and Prestrude (1977) extended the results of the latter study. It was found that there was a decrease in the percent of stimulus detections due to heating the stimulated area, and vice versa. In other words, there appeared to be a near-linear relationship between punctate pressure sensitivity and temperature change.

An interaction between temperature and vibratory sensitivity has also been reported. Marks, Stevens, and Tepper (1976) demonstrated that the threshold for the detection of two 1.0 sec vibratory bursts, one on each side of the forehead, was less than that for the detection of a single burst, even when the two were separated by as much as

0.75 sec! The fact that these stimuli were produced by warmed contactors lends credence to the interaction supposition, with regard to a spatial summation effect. Furthermore, it was shown that two successive 2.0 sec bursts (again, on opposite sides of the forehead) felt just as warm as a single 4.0 sec burst, implying an interaction effect with regard to temporal summation, as well.

For punctiform vibratory stimuli of 100, 256, and 900 Hz, the threshold appeared as a U-shaped function of temperature, with a minimum at 37°C (Weitz, 1941). Fucci, Crary, and Wilson (1976) pointed out that this value was approximately that of normal body temperature measured orally. Was temperature to be a determining factor of lingual vibrotactile thresholds, also? After the obtaining of six prethreshold measures, subjects were instructed to drink an 8 oz cup of water heated or cooled in random 10° steps ranging from 17-57°C. Vibratory stimuli of various frequencies were then applied. The point of normal body temperature measured orally was concommitant with the minimal lingual vibrotactile threshold. Furthermore, the difference between pre- and post-temperature thresholds increased with either increases or decreases in temperature. Green (1977) attempted to ascertain whether skin temperature effected vibration sensitivity in the dual-receptor populations in a similar manner. Using a water bath to control the skin temperature, vibratory stimuli were applied to the web of tissue between the

thumb and the index finger. A range of temperatures and frequencies (20-40°C; 30-250 Hz) were tested in two experiments. Results indicated two general functions: one at low frequencies which was temperature-dependent. This latter function assumed a U-shape with a minimum between 34-37°C. Sensitivity decreased with 150 and 250 Hz stimuli, but slightly increased with 30, 50, and 80 Hz stimuli when the skin was cooled to 20°C; warming produced a reduction in sensitivity to vibratory stimuli at each of the frequencies.

The techniques of the latter studies were such that confounds were not impossible. In the Fucci, et al (1976) procedure, subjects drank a cup of water in order to heat or cool the surface of the tongue. However, surface temperature of the tongue was not determined, or if so, was not mentioned. This would seem to be a necessity in reasearch of this type, for the surface temperature of the exposed tongue should quickly return to physiological zero. Therefore, one cannot rely on Fucci's, et al data to depict the actual temperature of the surface of the tongue in the measurements cited.

With regard to the following considerations, the Weitz (1941) and the Green (1977) studies will be discussed in more detail. The first parameter of concern is the site of stimulus application. Weitz used both the dorsal and the volar forearm in his study, using the latter when the former could not be sufficiently shaved. In other words, the data represented measurements averaged from both sites. Green used a

rather novel stimulus site. Due to his technique, the only easily applicable tissue was the web of skin between the thumb and the index finger. Little is known about the receptor populations in this region; no prior work had been done using this particular site.

The sizes of the contactors employed are also of concern. Weitz used a small sewing needle (.0006 cm^2 in area), while Green sought to approximate the contactor size of Weitz by using a steel pin with a flat surface area of .008 cm^2. Verrillo (1963, 1965) and Stevens and Green (1968) have shown that small contactor sizes do not produce very reliable results with regard to thresholds as a function of both temperature and frequency; therefore, it is highly unlikely that the small contactor sizes used by Weitz and by Green could produce reliable interactions between the temperature and the vibrotactile modalities.

The number of subjects in Weitz's and Green's studies are of major concern. Weitz used 6 subjects in the main portion of his study- 4 of these subjects were male and 2 of the subjects were female; Green's study utilized 3 subjects- 2 females and 1 male. Female subjects have been shown to fluctuate in their respective temperature sensitivity corresponding to fluctuations in hormone levels (Kenshalo, 1966). Taking into account this consideration only the males should be considered as reliable subjects, which would limit the number of reliable subjects to 4 in Weitz's case,

and to 1 in Green's (this subject did not even participate in the main experiment!). Perhaps Weitz's and Green's functions reflect sampling error.

Lastly, Green's technique leaves much to be desired. Subjects were tested with their arms immersed in a water bath; the stimulus site was apparently above the surface of the water. It would be difficult to imagine the vibrations of the stimulus not being conducted via the surrounding tissue to the water, and consequently to a large portion of the submerged skin surface. If this were the case, the effect of the water bath would have been a dampening of the vibratory sensations. Indeed this appeared evident in Green's Figure 1 (p. 244), in which he compared normal "dry" thresholds recorded at 30-31^{o}C to "wet" thresholds recorded at 37^{o}C (for which the skin should have a lower threshold), at various frequencies. At each frequency tested, the latter threshold was in fact higher than the former. And yet, Green concluded that the water bath seemed to have an effect which was "not large" on the subject's vibratory threshold!

The intent of the present study is to replicate the purpose but not the procedure of the Green (1977) study. The present technique will utilize methodologies from "dry" as opposed to "wet" experiments regarding vibrotactile stimulation and thermal sensitivity. A summary of the literature cited thus far is found in Table I.

Table I. Summary of the literature cited thus far in the study. Several works were omitted due to the condensed form of the table.

Investigator(s)	Subjects and Site	Results
Verrillo & Schmiedt (1974)	Human Glabrous	Free Nerve Endings- Rapidly-Adapting; Pacinians- Slowly Adapting.
Catton (1962)	Frog Tissue	A, B, C (vibratory), and D fibers.
Johansson (1976)	Human Glabrous	RA, SA I, PC (vibratory), and SA II units.
Verrillo (1968)	Human Glabrous, Hairy, Mucocutaneous	Dual-Receptor Mechanism- Pacinians and ?
Sato (1961); Talbot, Darian-Smith, Kornhuber, & Mountcastle (1968); Lindblom & Lund (1966)	Mesentery of Cat Monkey Glabrous	Pacinians (150-200 Hz). Dermal Nerve Net (30-40 Hz).
Douglas & Ritchie (1962); Maruhashi, Mizuguchi, & Tasaki (1952); Iggo (1959)	Mammalian Tissue	C Fibers (Temperature and Mechanoreception).
Green (1978)	Human Hairy, Glabrous	Localization Error and Two-Point Threshold- Lower (Cold); Higher (Warm).
Stevens, Green, & Krimsley (1977)	Human Glabrous	Punctate Pressure Threshold- Constant (20-40°C); Decrease Above and Below.
Prestrude & Kash (1972); Johnstone & Prestrude (1977)	Human Hairy	Punctate Pressure Sensitivity- Decrease (Warm); Increase (Cold).
Weitz (1941)	Human Tissue	U-Shaped Vibratory Threshold- Minimum at 37°C.
Fucci, Crary, & Wilson (1976)	Human Mucocutaneous	U-Shaped Vibratory Threshold- Minimum at 37°C.
Green (1977)	Human Glabrous	U-Shaped Vibratory Threshold- Minimum at 34-37°C; Flat Threshold.

METHODS

Subjects

Twelve male subjects participated in all phases of the study, with the exception of two subjects (A. P. and B. v. H. G.) who did not participate in the pilot studies. Each subject received a dry run of the technique to familiarize him with the apparatus and procedure. This was done to ensure more precise threshold measurements (Fucci, McCaffrey, Curtis, and Blackmon, 1974). Subjects remained naive as to the purpose of the study until after its completion.

Apparatus

The apparatus consisted of a Bruel and Kjaer (type 4810) Mini-Shaker (see Appendix I) which was mounted via an L-shaped aluminum bracket to a standard lathe tool post which could be advanced or retracted by small increments. The vibrator assembly was attached to a 3.43 cm diameter iron pipe. The mini-shaker was driven by a Hewlett-Packard (model no. 200AB) Audio Oscillator, whose output passed through a Hewlett-Packard (model no. 350D) Attenuator. Calibration of the Audio Oscillator was afforded by producing vibrations via the contactor through a phonograph cartridge hooked up to a Hewlett-Packard (model no. 1220A) Oscilloscope.

The vibrator and pipe assembly was attached to a wooden table whose legs were adjusted to provide a level surface.

Gasket material was used at all junctures of the apparatus to aid in dampening intrinsic vibrations. The assembly itself had two mini-levels (no. GML5, Great Neck Saw Mfrs., Inc.) glued to the upper surface of the aluminum bracket immediately over the mini-shaker which served to ensure uniform, level stimulations. A piece of 2.45 cm thick foam was placed along one side of the table underneath the mini-shaker, upon which rested a plaster mold used to cradle the subject's arm. The foam dampened out any additional vibrations produced by the apparatus or the building; the plaster mold provided level support for the arm of the subject in order to prevent fatigue and body movements. Subjects were seated comfortably in a dental chair.

A Southwest Technical Products Corporation Digital Multimeter produced a circuit between the vibrator tip and the skin surface which allowed precise indication of the point of contact between the tissue and the stimulus. A telegraph key was placed in the vibrator-attenuator circuit so as to allow the experimenter manual control over brief, successive stimuli.

A pair of earphones was used to eliminate background noises and apparatus noises (especially the hum of the mini-shaker). Extraneous noise of the vibrator, especially at suprathreshold intensities, has been shown to effect vibratory threshold levels. To mask this extraneous noise, many studies have used earphones for the subjects through

which narrow-band or wide-band noise was evident. Verrillo and Capraro (1975) have shown that the use of narrow-band/ low noise (15-48 Hz) stimulated the non-Pacinian system, and wide-band noise (2.0-4,800 Hz) stimulated both systems (depending on the contactor size). Therefore, the present study used earphones through which no masking noise was heard; however, these earphones did attenuate the intrinsic noise of the apparatus, as evident from the results of the first pilot study.

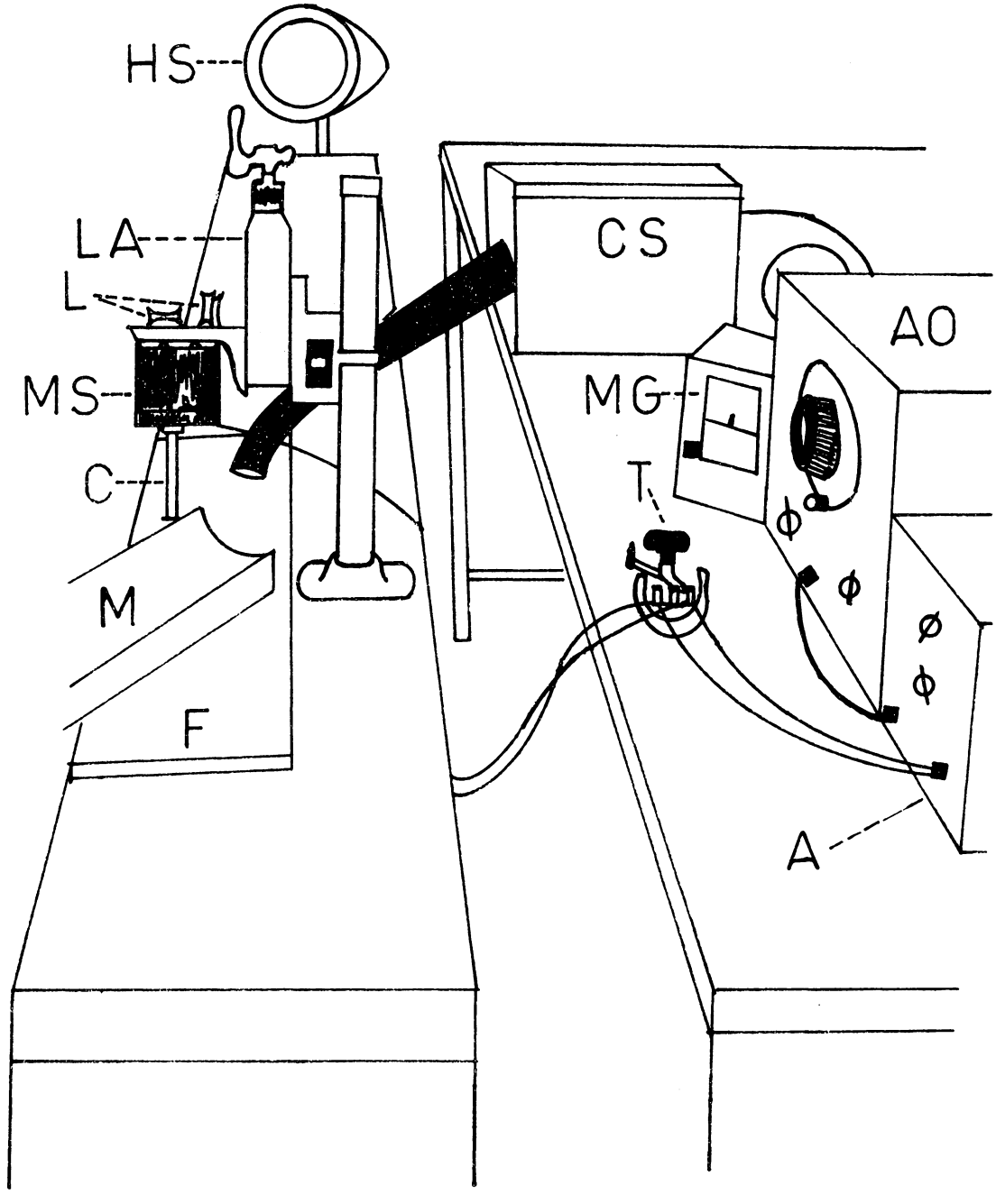
A Cole-Parmer (model 148) Minigraph kept an accurate record of the subject's skin temperature, via a thermode taped to the subject's index fingertip which remained as close to the stimulus site as possible throughout the session. The heat source was a 110V Westinghouse heat lamp. There has been some debate as to the use of infrared vs the use of microwave radiation for heat stimulation of cutaneous tissue. The argument stemmed from the fact that microwave radiation penetrated the skin up to a depth of 2.0 mm or so, while infrared radiation was absorbed by the first 0.1 mm of epidermis. How could infrared be stimulating the receptors which lie 0.3-0.5 mm deep? Vendrick and Vos (1958) showed that infrared heating produced the same effects as microwave heating. It appeared that the surrounding tissue conducted the heat beyond the point of absorption, thus reaching the receptors for indirect stimulation. However the skin is warmed or cooled, the receptors respond to

changes in the circumjacent tissue (Lowenstein, 1966). Infrared heat was chosen to provide stimulation since it was less of a health hazard, less cumbersome, and more economical. The cold source was a stream of CO_2 cooled air directed through a flexible rubber hose to the skin surface via a blower. A diagram of the apparatus is shown in Figure 3.

Procedure

All stimuli in the actual study were applied to the right middle fingertip; frequencies used were: low- 40 Hz, high- 160 Hz. These values were determined as the result of a second pilot study (see Fig. 4). In Figure 4, group means from 10 subjects were plotted representing thresholds in decibels attenuated as a function of frequency; each point represents 40 observations- 4 observations per subject. According to the data, the fingertip was more sensitive than the thenar eminence which was more sensitive than the volar surface of the forearm. This was consistent with Verrillo's (1974) finding without the use of a surround. Furthermore, Figure 4 shows that the dorsal forearm was slightly less sensitive than the volar forearm to frequencies of 160 Hz and above (see Gilmer, 1937), yet slightly more sensitive to frequencies of 80 Hz and below. With regard to frequency, the 40 Hz stimuli produced a lower threshold than the 30 Hz or the 25 Hz stimuli at each of the sites. Both the thenar eminence and the fingertip showed maximum sensitivity to 160 Hz stimuli, while the dorsal and volar forearm showed

Figure 3. Diagram of the vibratory apparatus. Shown are: M- mold for positioning arm; F- foam padding for dampening vibrations; C- contactor; MS- mini-shaker; L- levels; LA- lathe assembly; T- telegraph key; MG- minigraph; AO- audio oscillator; A- attenuator; HS- heat source; and CS- cold source.


HS
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maximum sensitivity between 80 and 160 Hz. All four sites showed subsequent declines in sensitivity to frequencies above 160 Hz (Sato, 1961; Lindblom and Lund, 1966; Talbot, Darian-Smith, Kornhuber, and Mountcastle, 1968; Verrillo, 1968).

In the actual study seven temperatures were tested at each of the two frequencies for all subjects: 31-32°C (physiological zero) and ± 4, 8, and 12°C, providing a temperature range of 19-44°C. Room temperature was carefully monitored throughout the study via a thermometer. Room temperature remained fairly constant, fluctuating no more than 3 degrees throughout the study.

The size of the contactor has been shown to effect vibratory thresholds (see p. 15). The two factors- contactor size and frequency- appear to be interdependent: When very small contactors are used, the effects of frequency wash out; when very low frequencies are used, spatial summation is absent. For this reason a contactor size of 1.96 cm^2 (no surround) was used.

Contact of the stimulus to the skin was indicated via the digital multimeter, after which the contactor was further lowered a distance of 1.0 mm to ensure continuous contact with the skin surface. Subjects acknowledged a felt stimulus by saying, "O. K." Subjects wore earphones on all trials and were instructed to relax and look straight ahead, not at the apparatus.

A session consisted of all trials at and above 32°C or those below 32°C. A total of 10 ascending series of the method of limits were run at each temperature- 5 series per temperature per session. In other words, subjects ran four sessions apiece: 2 sessions each consisting of 5 trials at each temperature below 32°C; 2 sessions each consisting of 5 trials at each temperature at and above 32°C. Skin temperatures were monitored via the minigraph. Sessions for each subject were run up to 10 days apart, at the same time each day.

RESULTS

The data, as shown in Figure 5, indicate the following results: 1) there is a general increase in sensitivity to low frequency vibratory stimuli with increases in temperature, and 2) with high frequency stimuli there is also a linear increase in vibratory sensitivity with increases in temperature. The latter result is contrary to the work of Weitz (1941) and Green (1977), who reported U-shaped thresholds as a function of temperature for high frequency vibrations. While our high frequency function in Figure 5 appears slightly curvilinear, a trend analysis of the data for the effect of temperature yielded significant linear trends (alpha=.05, $F_{(6,154)}=86.07$), but no significant quadratic trends.

Group means are plotted in Figure 5 representing threshold in decibels attenuated as a function of temperature in degrees Centigrade. Each data point represents the average of 10 observations for each of the 12 subjects recorded during 24 sessions.

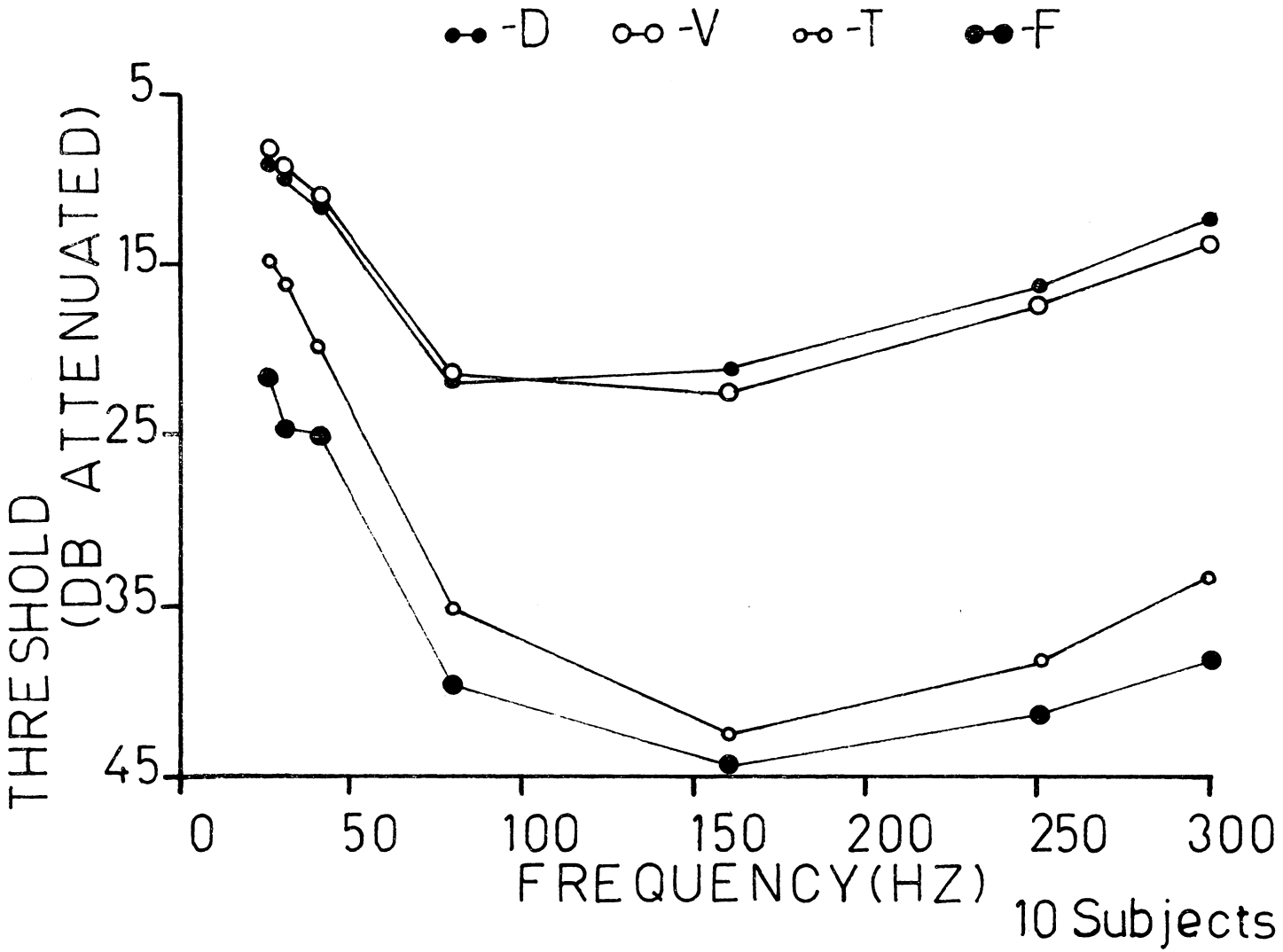
An analysis of variance was performed on the data. A significant effect of stimulus frequency (alpha=.05, $F_{(1,154)}=637.50$) was obtained. As evident from Figure 5, 40 Hz vibration produces a relatively high threshold, averaging no more than 23 decibels of attenuation across the range of temperatures. Threshold appears much lower for high frequency vibration, resulting in values of no less than

38 decibels of attenuation.

With regard to temperature effects, the following can be seen from Figure 5: For low frequency stimuli the total change in sensitivity from 20°C to 44°C is a 3.4 decibel increase. The greater amount of this change occurs between 20°C and 36°C (about 3 decibels). At temperatures above 36°C the function appears to level off at roughly 23 decibels of attenuation, producing an increase of only one-third of a decibel between 36°C and 44°C. For high frequency stimuli, the total change in sensitivity was about a 5 decibel increase occurring between 20°C and 44°C. Between 40°C and 44°C the threshold rises almost half of a decibel. Maximum sensitivity occurs, apparently, between 36°C and 40°C, probably closer to the latter, beyond which sensitivity decreases. The result is similar to Green (1977), who reported, using a 150 Hz vibration, a U-shaped threshold with maximum sensitivity at 37°C. The present results show that minimum sensitivity occurs at temperatures below 28°C (also in line with Green's results), producing about a 4 decibel decrement from 28°C to 20°C.

Figure 6 represents the means of the data from the 12 subjects for each of the two pairs of sessions, and is included as a reliability measure. As the data indicate, with the exception of those points at 32°C and 36°C for 40 Hz stimuli, each pair of points differs by no more than 1 decibel of attenuation. Those at 32°C differ by 2.5 decibels, and those at 36°C differ by 1.5 decibels. Moreover, the measure-

Figure 4. Data from the second pilot study for 10 subjects. Threshold for vibratory sensitivity is shown in decibels attenuated as a function of frequency in Hz. Small closed circles represent measurements from the dorsal forearm, small open circles- from the thenar eminence, large closed circles- from the middle fingertip, and large open circles- from the volar forearm. Frequencies tested were 25, 30, 40, 80, 160, 250, and 300 Hz.


-D
-V
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THRESHOLD (DB ATTENUATED)
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15
25
35
45
0
50
100
150
200
250
300
FREQUENCY(HZ)
10 Subjects

Figure 5. Vibratory threshold as a function of skin temperature for 12 subjects. Threshold is represented in decibels attenuated as a function of seven skin temperatures: 20, 24, 28, 32, 36, 40, and 44°C. The upper function was obtained using 40 Hz stimuli, the lower by using 160 Hz stimuli.

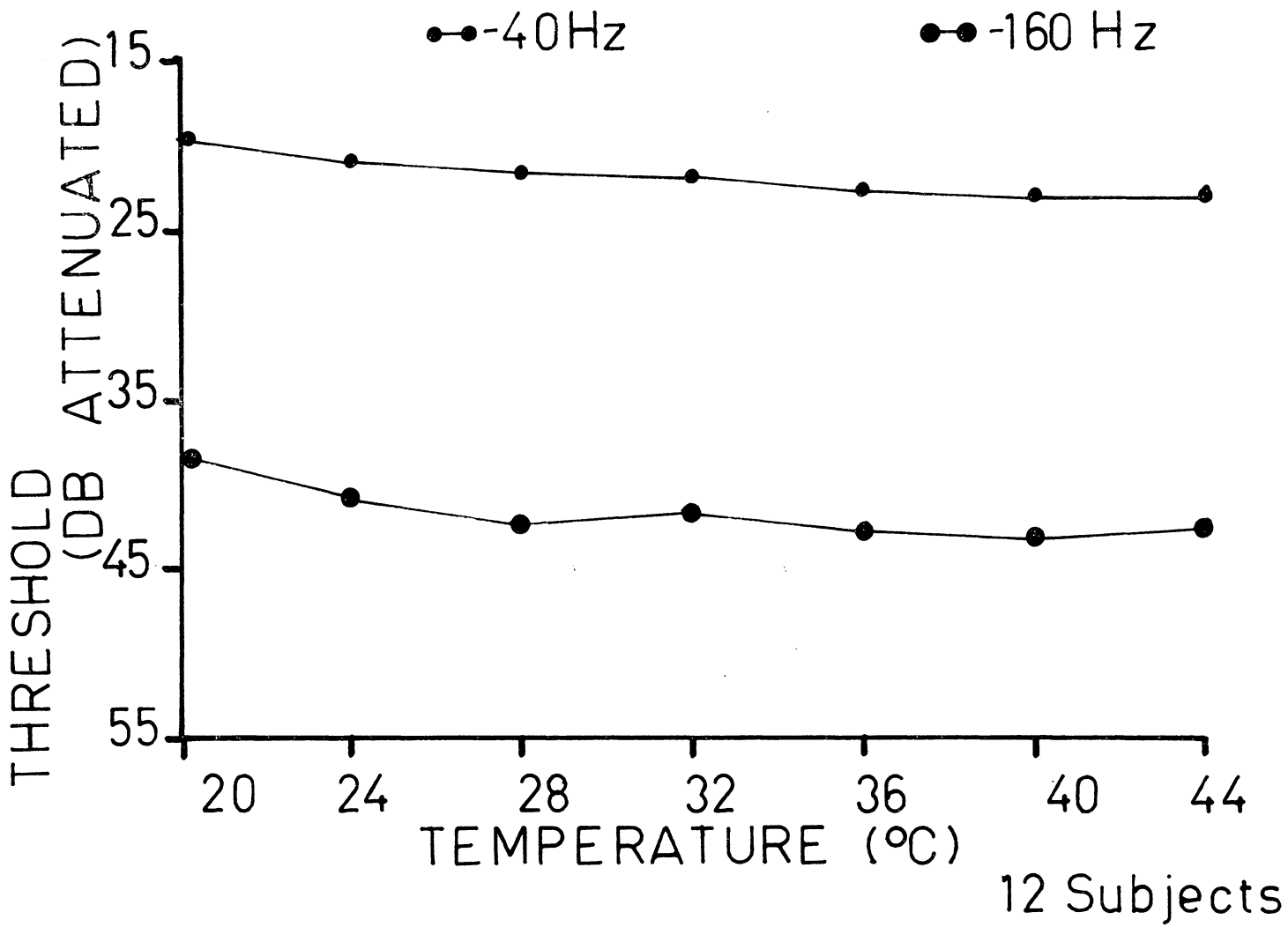

-40Hz
-160 Hz
THRESHOLD (DB ATTENUATED)
15
25
35
45
55
20
24
28
32
36
40
44
TEMPERATURE (°C)
12 Subjects

Figure 6. Comparison of thresholds between sessions. Data represent vibratory thresholds as a function of temperature for 12 subjects. Filled circles represent observations averaged from the first sessions at both high and low temperatures for all subjects, open circles represent like data from the second sessions for all subjects. The upper function depicts threshold for 40 Hz stimuli, the lower for 160 Hz stimuli.

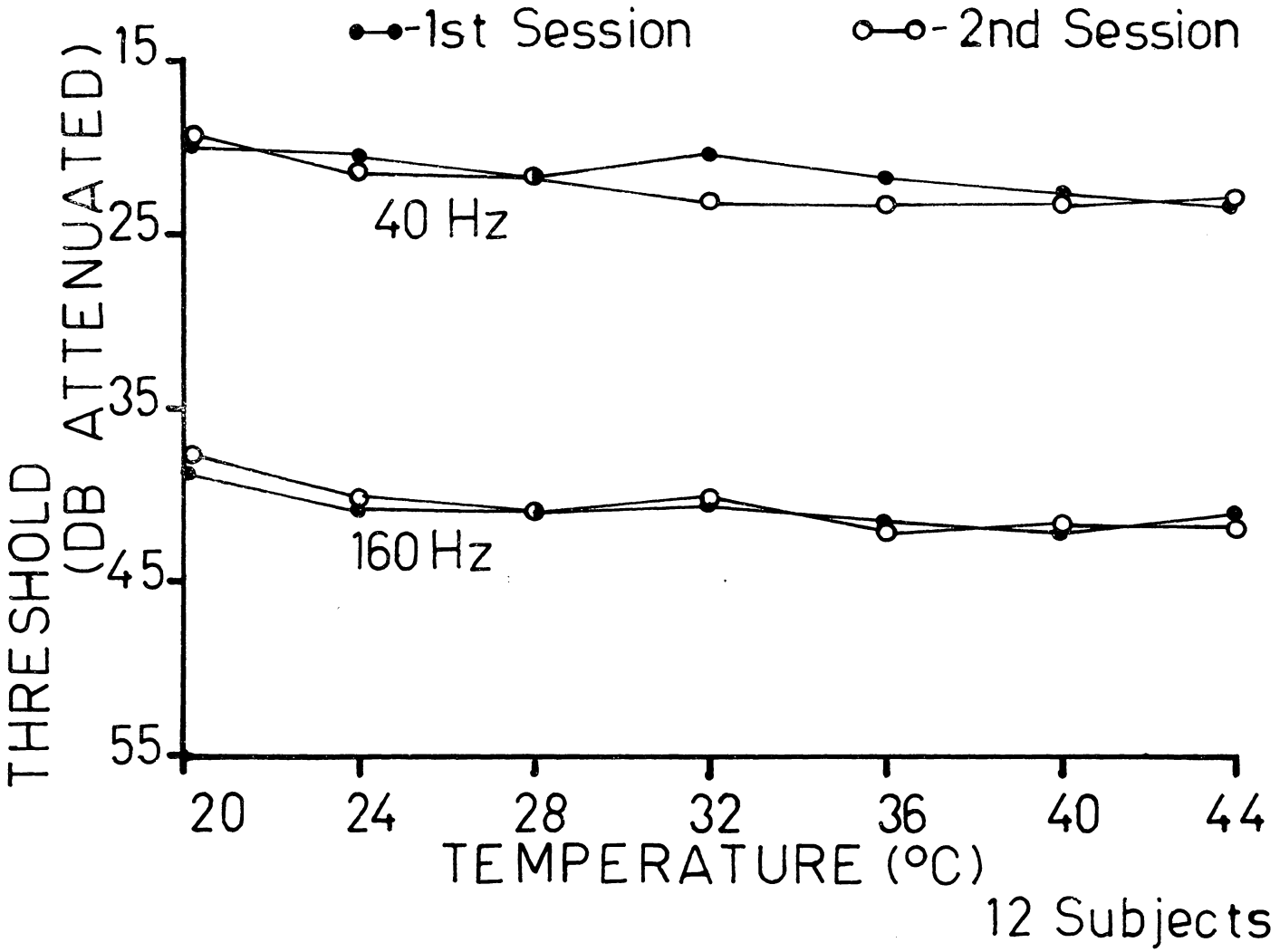

1st Session
2nd Session
THRESHOLD (DB ATTENUATED)
15
25
35
45
55
40 Hz
160 Hz
20
24
28
32
36
40
44
TEMPERATURE (°C)
12 Subjects

Figure 7. Pilot data from subject #2. Small filled circles represent thresholds measured on the dorsal forearm, small open circles- from the thenar eminence, large closed circles- from the middle fingertip, large open circles- from the volar forearm.

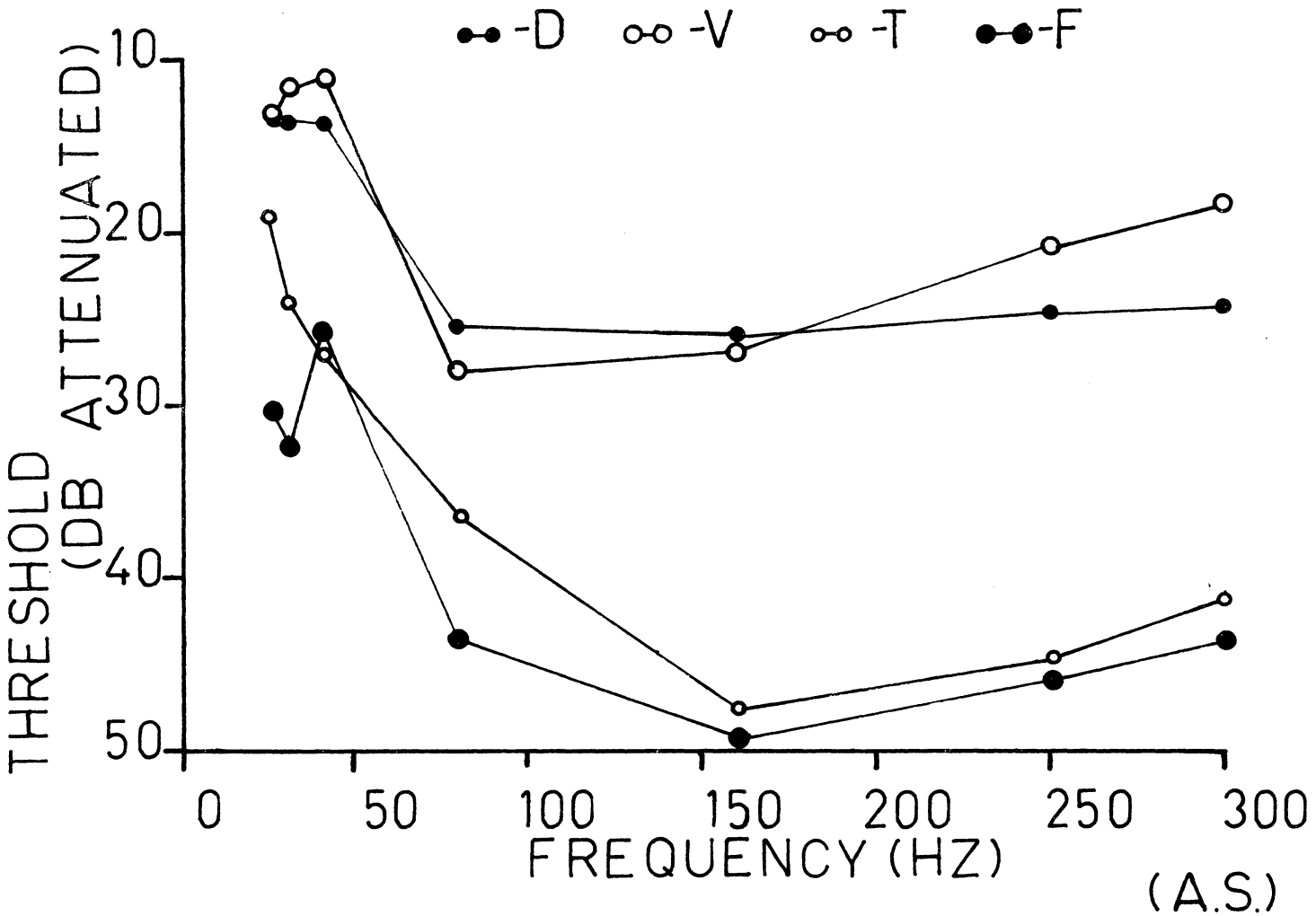

-D
-V
-T
-F
THRESHOLD (DB ATTENUATED)
10
20
30
40
50
0
50
100
150
200
250
300
FREQUENCY (HZ)
(A.S.)

Figure 8. Data from the actual study from subject #2. Upper function represents threshold for 40 Hz stimuli, lower for 160 Hz stimuli.

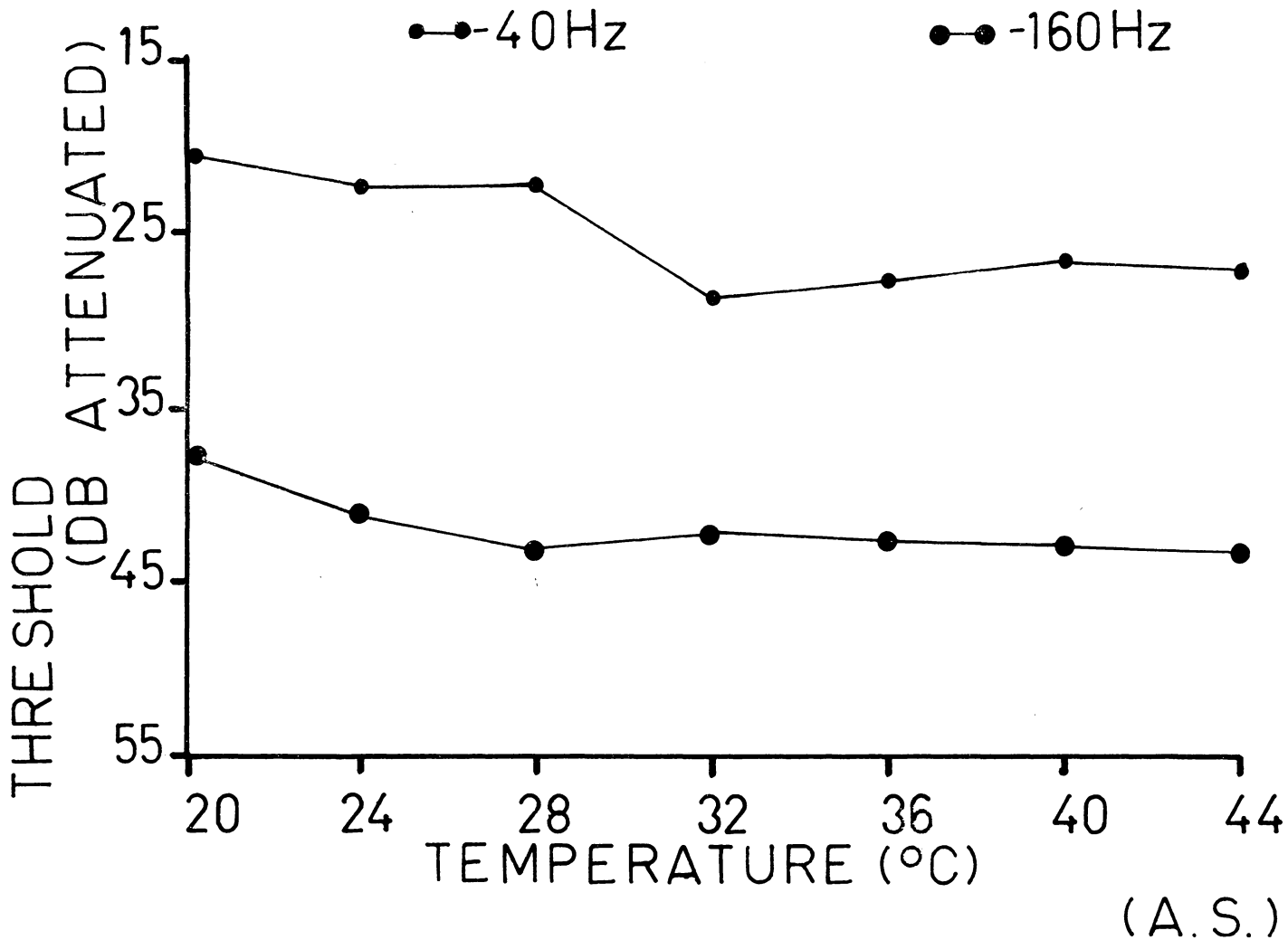

-40Hz
-160Hz
THRESHOLD (DB ATTENUATED)
15
25
35
45
55
20
24
28
32
36
40
44
TEMPERATURE (°C)
(A.S.)

Figure 9. Pilot data from subject #10. Small closed circles represent thresholds measured from the dorsal forearm, small open circles- from the thenar eminence, large closed circles- from the middle fingertip, large open circles- from the volar forearm.

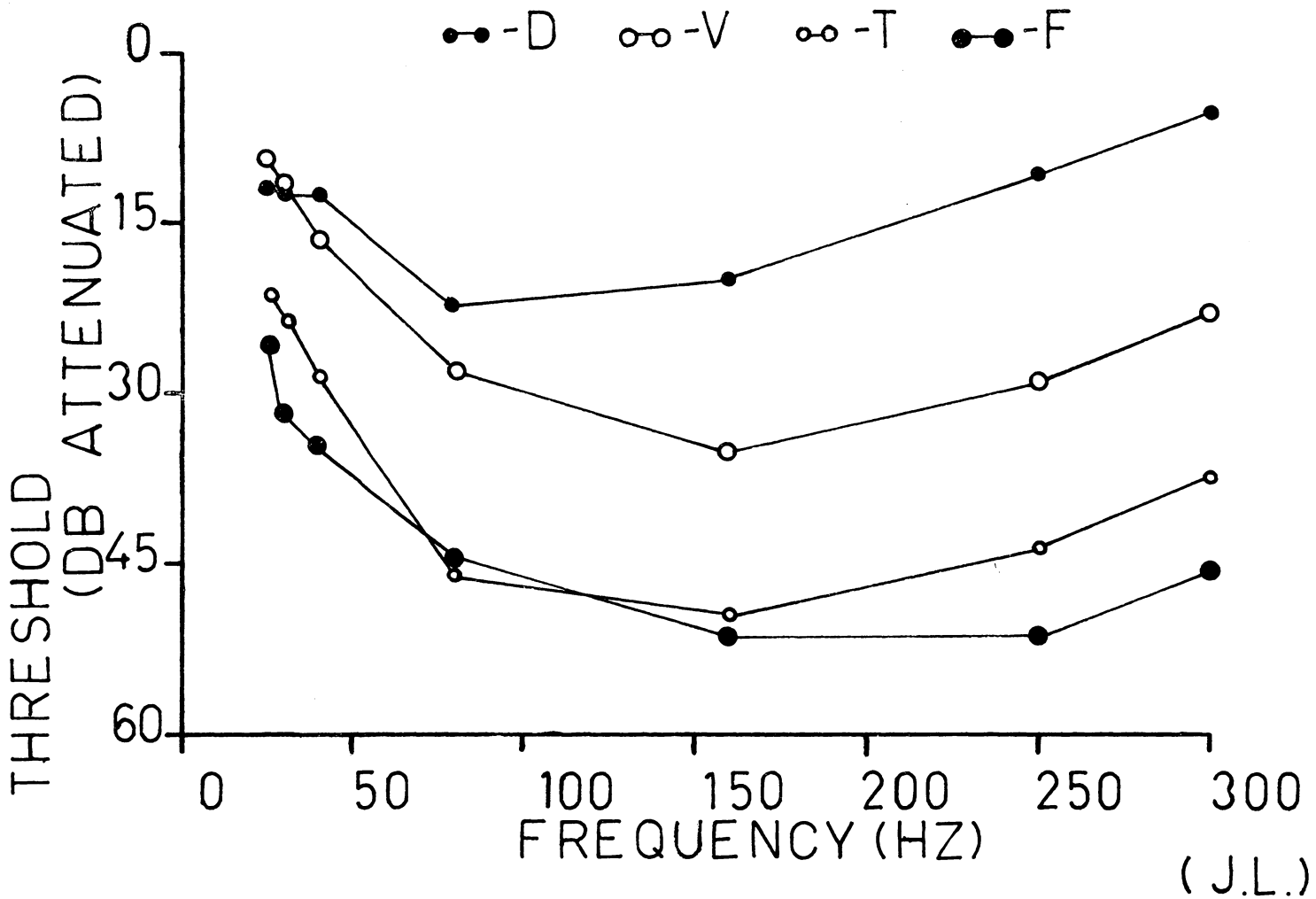

-D
-V
-T
-F
0
15
30
45
60
THRESHOLD (DB ATTENUATED)
0
50
100
150
200
250
300
FREQUENCY (HZ)
(J.L.)

Figure 10. Data from the actual study from subject #10. Upper function represents vibratory threshold using 40 Hz stimuli, lower- threshold using 160 Hz stimuli.

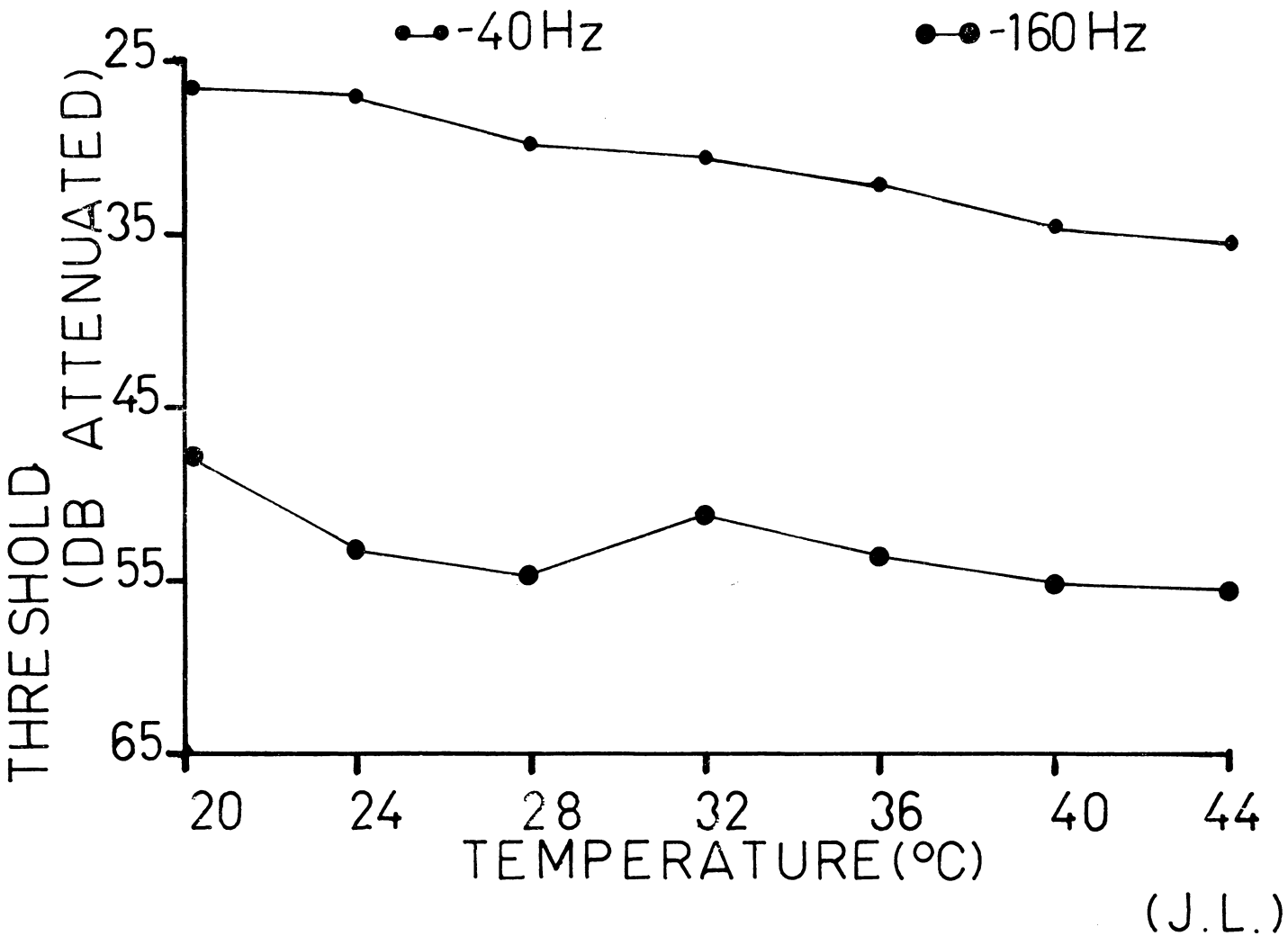
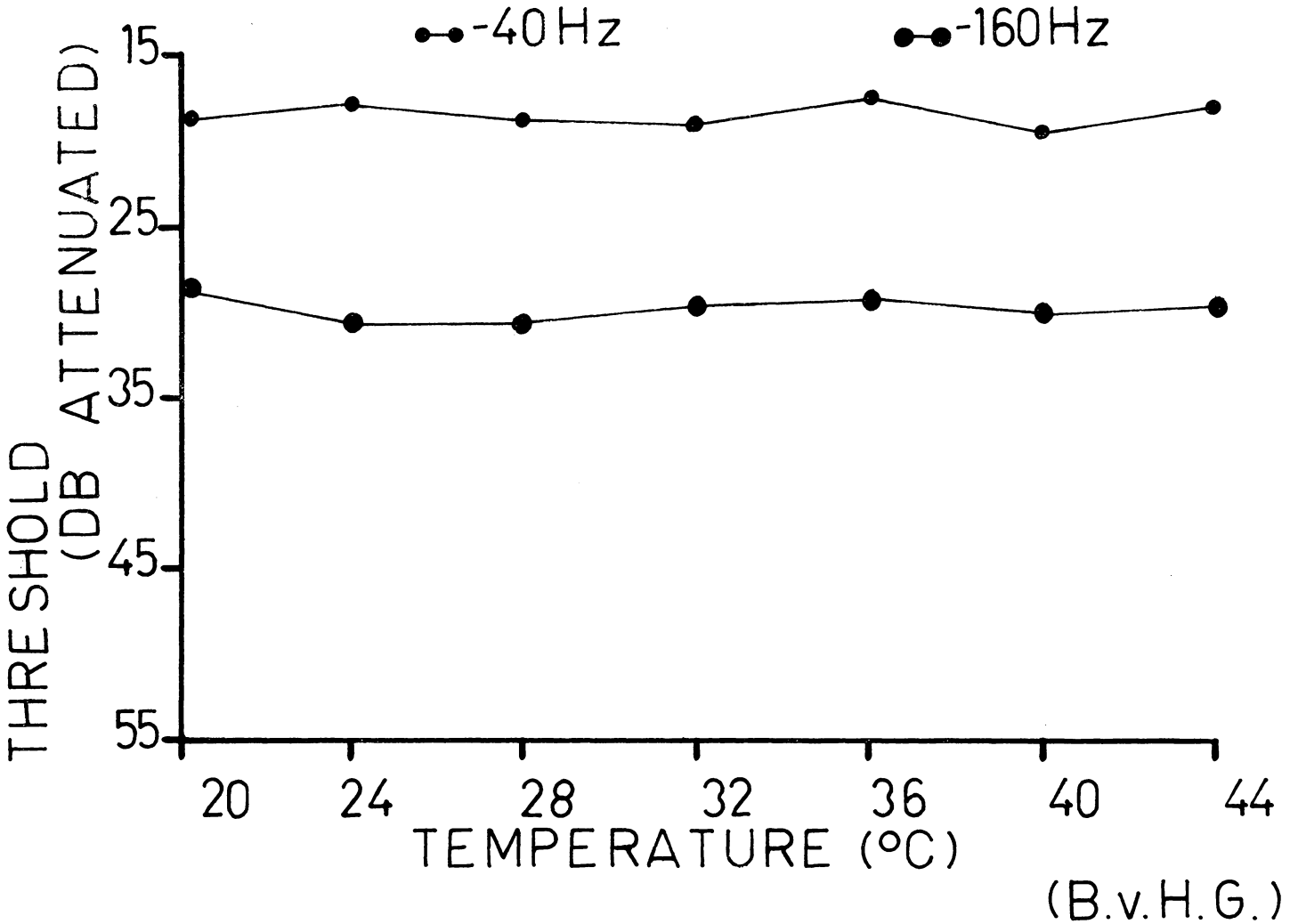

-40Hz
-160Hz
25
35
45
55
65
THRESHOLD (DB ATTENUATED)
20
24
28
32
36
40
44
TEMPERATURE (°C)
(J.L.)

Figure 11. Data from subject #12 from the actual study. Upper function represents threshold for 40 Hz stimuli, lower for 160 Hz stimuli.


-40Hz
-160Hz
15
25
35
45
55
THRESHOLD (DB ATTENUATED)
20
24
28
32
36
40
44
TEMPERATURE (°C)
(B.v.H.G.)

ments between sessions for both frequencies at 28°C yield identical means, while those at 24°C and 32°C for 160 Hz and those at 44°C for 40 Hz yield differences of about 0.2 decibels. Therefore, with the exception of the points at 32°C and 36°C for low frequency stimuli, all points attest to a high degree of reliability between sessions. (Each of these points represents 60 observations.)

Figure 7 represents the data of subject #2 (A. S.), age 21, from the second pilot study, and Figure 8 depicts data from the same subject in the actual study. The subject was the only black who participated in the study. The subject's low frequency thresholds for the fingertip are well below the group means (for 25 Hz and 30 Hz). Figure 8 shows that for stimuli of 40 Hz at temperatures at and above physiological zero, the subject's threshold is much lower than the group mean. Also, the overall difference between 20°C and 44°C thresholds for this subject, 7.6 decibels, is far above the average difference.

Figures 9 and 10 represent similar data from subject #10 (J. L.), age 20; this subject was extremely fair-skinned. For 40 Hz stimuli, Figure 9 shows a much lower threshold for this subject as measured through the fingertip. Figure 10 magnifies this effect across temperatures, with the subject's threshold at 20°C being 26.5 decibels, and 35.4 decibels at 44°C, for a difference of 8.9 decibels (which is far above the average, as well). Figure 9 also

reveals a high degree of variability with the high frequency stimuli with respect to the group means in Figure 4. Furthermore, subject 10's data from Figure 10 show a high degree of difference from the group data. Threshold measurements are again lower than group averages and a difference of about 8 decibels appears between points at 20°C and 44°C, once more higher than average.

The data of subject #12 (B. v. H. G.), age 69, are shown in Figure 11; this subject did not participate in the pilot study. It is interesting to note that the thresholds for both high and low frequency stimuli are higher than group thresholds, high frequency thresholds moreso. Also, total change in sensitivity across the temperature range is smaller than the group average, being just 0.6 decibels and 1.1 decibels for 40 Hz and 160 Hz stimuli, respectively. In fact, neither threshold shows an increase in threshold sensitivity across temperatures proportional to that of the group increases.

DISCUSSION

In cutaneous research, two 'camps' have developed; these camps may be distinguished by their methodologies. The first believes that the cutaneous receptors must be isolated from the surrounding tissue in order for the effects attributed to the receptors to be genuinely understood. Such methodologies include *in vivo* neural recordings from isolated receptors (Iggo, 1960) or, when total isolation is not feasible, the use of a surround device which limits the spread of stimulation (e.g. vibration) to the surrounding skin surface (Verrillo, 1968). This latter procedure thus isolates stimulation to a small area. The second camp regards the skin itself as an implicit part of the receptor mechanism, one which cannot and must not be ignored. Such methodologies utilize the skin surface in their technique without using limiting surrounds (Green, 1977), while explanations of results thereof are in terms of the cutaneous organ as a whole (Johnstone and Prestrude, 1977; and others). The present study, due to its methodology, adopted the latter standpoint.

The present results indicate that there is a general linear increase in sensitivity to vibratory stimuli with increases in temperature from 20°C to 44°C; this effect appears for both the high frequency and the low frequency receptor populations. Although a rise in threshold occurred

for 160 Hz stimuli from 40°C to 44°C, this decrease in sensitivity is not statistically significant. This result is contrary to previous work in the area by Weitz (1941); Fucci, Crary, and Wilson (1976); and Green (1977). All of these studies reported findings of a U-shaped function for high frequency vibrations, with minima between 35-38°C. In other words, sensitivity to high frequency vibration decreased at temperatures above about 37°C. Why should the present results be any different?

The present study differs from the Weitz and the Green studies with regard to the considerations discussed previously (see pp. 14-16). (The Fucci, et al. study will not be contrasted due to the absence from it of any measurements of skin surface temperature.) Unlike the Green data, ours reflect measurements from a previously studied stimulus site in which the receptor populations have been identified. Our data do support Weitz's choice of stimulus sites, though. Figure 4 shows about a 0.5 decibel difference between volar and dorsal forearm thresholds across frequencies; there seems to be little difference between which of the two stimulus sites is used. With respect to contactor size, the present study utilized a steel pin much like that used by Green, but with a contactor area roughly 245 times that of Green's! The present data then, may reflect a much higher degree of spatial summation than the data of Weitz and of Green, which reduces the effect of temperature. The decreases in thresholds at

high temperatures in prior work may have been artificial ones produced by small contactors. A further difference between the present and previous studies is the number of reliable subjects used- the number in the present study was three times that of Weitz, and twelve times that of Green! Furthermore, our subjects were shown to be reliable between sessions separated by up to 10 days. A final concern is the number of observations represented by each of Green's data points in his Figure 5 (p. 246), which depicted threshold as a function of temperature. Each point represented 15 measurements, one observation per condition per subject repeated in each of five sessions. Our points in Figure 5 (threshold vs temperature) represent five observations per subject recorded on each of two sessions, for a total of 120 observations per point! With all these considerations in mind, it is little wonder that differences appear between the present results and those of Weitz and Green. Moreover, the present data may be considered to have a much higher degree of reliability than previous data.

The upshot of the present work (with respect to the above considerations) should be to perform a more systematic investigation on vibrotactile sensitivity by varying stimulus site, frequency, contactor area, temperature, and surround vs no surround, while using reliable subjects. "Reliable subjects" refers not only to males, however; female data are of equal importance. Yet females should participate only at

various coincidental stages of their respective ovulation cycles when temperature is used as an independent variable.

The present procedure is not without its own considerations. The air blower did produce CO_2 currents upon the site of stimulation; however, only 2 of the 12 subjects reported any noticeable vibrations produced by the currents, and one of these subjects also reported that the stimulus vibrations were still quite easily and exclusively detectable. Perhaps more accurate control of stimulus duration is warranted than the use of a telegraph switch. Yet the author had sufficient practice with the technique prior to the second pilot study. The stimuli used lasted no longer than 1 sec apiece. Finally, the stimulus was not marked by ink or any other means. But given the relatively small size of the fingertip and the homogeneity of the receptors within, some control over stimulus location was afforded. Also, the author took great care in utilizing the same relative site on each subject's fingertip in order to aid in subsequent relocations.

There are several implications for future work in this area. Replications of the technique should test the interaction between contactor size and stimulus site. Also, contactors which are themselves heated or cooled (such as vibrating a Peltier refrigerator) could be used to stimulate the vibratory receptors. Other implications from the present work are at best speculative. One such speculation concerns the amount of skin pigmentation in an individual's epidermis

and his or her vibrotactile sensitivity. As seen in Figures 7, 8, 9, and 10, with respect to Figures 5 and 6, dark- and fair-skinned individuals who participated in the study showed larger differences in sensitivity with respect to group means to go unnoticed. Subject #2 (dark-skinned) appears to have a much lower sensitivity to low frequency stimuli at temperatures at and above physiological zero than the average sensitivity. Subject #10 (fair-skinned) shows a lower sensitivity to most frequencies, with a greater amount of differential sensitivity between stimulus sites, than the average. Also, across temperatures, this subject exhibits lower sensitivity to both high and low frequency stimuli.

Lastly, age may also be a factor regarding high frequency vibratory sensitivity in cutaneous tissue, as seen by comparing Figure 11 to Figure 5. Subject #12 (age 69) shows a much higher 160 Hz threshold across temperatures than the group average. In contrast to this, subject #11 (A. P.), age 45, did not exhibit this lower sensitivity at high frequencies. Apparently, a loss of sensitivity to high frequency vibration may be a function of cutaneous tissue of the elderly (beyond the age of 60 or so). This speculation does have substantive basis: Verrillo (1977) found that children (with a mean age of 10 years) showed greater sensitivity to vibratory stimuli than adults (mean age of 21 years). It is not too unrealistic to hypothesize a further decline in sensitivity with further increases in age;

according to the present results, this supposition is supported.

SUMMARY

It can be concluded that vibrotactile sensitivity increases with temperatures above physiological zero and decreases with temperatures below physiological zero. This linear effect of temperature occurs not only with low frequency stimuli but also with high frequency stimuli; the effect appears very reliable across sessions separated by as much as 10 days.

Individual differences occurred which were intriguing from a hypothetical standpoint. One such occurrence was that individuals with either extremely high or low amounts of skin pigmentation showed more sensitivity to vibratory stimuli than individuals with average amounts of skin pigmentation. Also, age might affect sensitivity to vibratory stimuli; increased age might result in a decrease in sensitivity to high frequency vibrotactile stimulation.

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APPENDIX I: APPARATUS SPECIFICATIONS

Vibrator: Bruel and Kjaer Mini-Shaker, type 4810.
Impedence: 3.5 Ohms.
Input Power: 15 VA max.
Stroke: $\pm$ 3 mm max.

Oscillator: Hewlett-Packard Audio Oscillator, no. 200AB.
Frequency Range: 20 Hz-18 kHz.
Amplitude Range: 0-100.
Output: 600 Ohms.

Attenuator: Hewlett-Packard Attenuator Set, no. 350D.
Input Power: 2W-55V.
Output: 600 Ohms.
Attenuation Range: 0-110 db.

Minigraph: Cole-Parmer Minigraph, no. 148.
Input Power: 110V.
Frequency: 60 Hz.

Multimeter: Southwest Technical Products Corporation
Digital Multimeter.
Functions: kOhm, DC MA, AC MA, DCV, ACV.
Range: 2-2,000.

Heat Source: Westinghouse Heat Lamp, standard.
Input: 110V.

Earphones: David Clark, Inc., Clark 300.

Mini-Levels: Great Neck Saw Mfrs., Inc., no. GML5.

Calibrating Standard: Hewlett-Packard Oscilloscope,
no. 1220A.

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THERMAL EFFECTS UPON HUMAN VIBRATORY SENSITIVITY

by

Jerome Edward Gundersheimer, Jr.

(ABSTRACT)

Vibrotactile sensitivity is measured using a "dry" procedure as opposed to a "wet" procedure previously used. Thresholds are determined using 40 Hz and 160 Hz stimuli across seven temperatures ranging from 20°C to 44°C. Twelve male subjects participated in each of four sessions, producing a high degree of reliability.

Results indicate that vibrotactile sensitivity increases with temperatures above 32°C and decreases at temperatures below 32°C; thresholds represent similar functions for both high and low frequency vibrotactile receptor populations. Concerns with previous studies are discussed. Implications are made with regard to future work in the area regarding skin pigmentation and subject age.