Chapter I. Introduction

This work was motivated by an interest in using the sense of touch as an alternative communication channel. The potential to receive information tactually is well illustrated by some natural (i.e., non-device related) methods of tactual speech communication. Particularly noteworthy is the so-called Tadoma method that is employed by some individuals who are both deaf and blind. In Tadoma, one places a hand on the face and neck of a talker and monitors a variety of actions associated with speech production. Previous research has documented the remarkable abilities of experienced Tadoma users (Reed, Rabinowitz, Durlach, Braida, Conway-Fithian, & Schultz, 1985); these individuals can understand everyday speech at very high levels, allowing rich two-way conversation with both familiar and novel talkers. Conversely, attempts to develop artificial tactual speech communication devices have had only limited success, with none achieving performance anywhere near that demonstrated by Tadoma (e.g., Reed, Durlach, Delhorne, Rabinowitz, & Grant, 1989).

One problem with most previous tactual devices concerns the nature of the output display. These displays have generally been composed of multiple stimulators that deliver high-frequency vibration to the tactile sensory system. Such "homogeneous" displays have few distinctive perceptual qualities. Furthermore, for practical and / or technical reasons, the displays have rarely engaged the hand, the most sensitive and richly innervated receiving site. In contrast, Tadoma is received by the hand and a talking face is perceptually rich, simultaneously displaying various stimulation qualities that engage both the kinesthetic and tactile sensory systems.

Recognition of the need for richer tactual displays has long been evident. With the aim of developing a tactual communication system, Bliss's "reverse-typewriter" system (Bliss, 1961) was capable of delivering motional pulses to the eight fingers of both hands (excluding the thumbs) that are similar to the motions made by typists. The Sensory Communication Group at MIT has developed an artificial mechanical face display, built around a model plastic skull (Reed *et al.*, 1985), that has shown promise in conveying information important in Tadoma (Leotta, Rabinowitz, Reed, & Durlach, 1988; Rabinowitz, Henderson, Reed, Delhorne, & Durlach, 1990). As a more general display for studying haptic perception by the hand, the "OMAR" system was recently described by Eberhardt, Bernstein, Barac-Cikoja, Coulter, & Jordan (1994). It was designed to deliver kinesthetic as well as tactile stimulation to one or more fingers. Nevertheless, none of these artificial displays has, thus far, been shown to be capable of delivering tactual stimulation that can be received by human observers at a rate comparable to that achieved by Tadoma users.

In order to develop a tactual display that can be used successfully for sensory substitution, we first need a tactual display that is designed to match the perceptual capabilities of human observers. We then need to explore ways of maximizing the information transmission capabilities of such a display by careful design of stimulus and response sets. Finally, the information transfer per presentation and the information transfer rate achievable with such a device must be measured, or estimated, with human observers. Simply stated, that is the goal of this research, to go through the process from hardware development through psychophysical evaluation.

In a preliminary study, the potential for communication through the kinesthetic aspect of the tactual sense was examined in a series of experiments employing Morse Code signals. A manuscript, entitled "Reception of Morse Code Through Motional, Vibrotactile, and Auditory Stimulation", has been submitted to *Perception&Psychophysics*. It is enclosed as an appendix to this thesis (Appen. A). For the main research in this thesis, a new multi-finger tactual display was developed (Chap. 2). We aimed at a continuous frequency response so that the perception from low-frequency large-amplitude motions (i.e., kinesthetic stimulation) to high-frequency small-amplitude vibrations (i.e., vibrotactile stimulation) could be studied as a continuum. We then explored ways of constructing stimulus and response sets that were optimized for information transfer, and measured information transfer achievable with human observers (Chap. 3). The information transfer rate achievable with the multi-finger tactual display was estimated (Chap. 4).

During the course of this work, several unresolved issues that are related to this research were identified and documented (Chap. 5). Finally, a general discussion including directions for future research is presented (Chap. 6).

I-1 Background

The following is a general review of literature on the tactile and kinesthetic senses, focussed on studies concerning the human hand. The objective is to provide a basic understanding of taction that is relevant to this thesis work. The emphasis is on positional / motional stimulation of the tactual sensory system.

I-1.1 Tactile Sense

Vibrotactile stimulation of the skin surface usually consists of low-intensity, high-frequency components. Literature on absolute detection, intensity and frequency discrimination, temporal resolution, and the Vibratese language (Geldard, 1957) is reviewed here.

Receptor Mechanism / Absolute Detection Threshold

Previous physiological and anatomical experiments have identified four afferent fiber types (PC or RA II, RA I, SA II and SA I) in glabrous (nonhairy) skin of the human somatosensory periphery. Johnson & Hsiao (1992) reviewed neural mechanisms of tactual form and texture perception and proposed the following working hypothesis: The SAI system is the primary spatial system and is responsible for tactual form and roughness perception when the fingers contact a surface directly and for the perception of external events through the distribution of forces across the skin surface. The PC system is responsible for the perception of external events that are manifested through transmitted high-frequency vibration of the kind that are critical in the use of objects as tools. The RA system is responsible for the detection and representation of localized movement between skin and a surface as well as for surface form and texture when surface variation is too small to activate the SA I afferents effectively. Srinivasan, Whitehouse, & LaMotte (1990) studied the mechanism of tactile detection of slip using glass plates. They found that direction of skin stretch (impending but not actual slip) was coded solely by the SAs (whether it was SA I or SA II was not clear, since the Macacca Fascicularis monkeys they used did not have SA II fibers). The detection of slip was possible only when the glass plate had detectable surface features. Different neural mechanisms were responsible for slip detection depending on the geometry of the micro-features of the glass surface (i.e., RAs for single-dot plate; and PCs for fine homogeneous dot matrix that induced vibrations of the skin). When the surface features are of sizes greater than the response thresholds of all the receptors, redundant spatiotemporal and intensive information from all three afferent fiber types might be available for the detection of slip.

There have been numerous psychophysical studies on the absolute detection threshold of vibrotactile stimulation and its physiological substrates (e.g., Bolanowski Jr., Gescheider, Verrillo, & Checkosky, 1988; Brammer, Piercy, Nohara, Nakamura, & Auger, 1993; Gescheider, O'Malley, & Verrillo, 1983; Gescheider, Sklar, Van Doren, & Verrillo, 1985; Gescheider, Verrillo, & Van Doren, 1982; Labs, Gescheider, Fay, & Lyons, 1978; Verrillo, 1963). Psychophysical evidence that four channels participate in the perceptual process was presented in Bolanowski Jr., *et al.* (1988). In a series of experiments involving selective masking of the various channels and modification of the skin-surface temperature, four psychophysical channels were defined: P (Pacinian), NP I (non-Pacinian I), NP II and NP III. Table I-1 summarizes the major findings in Bolanowski Jr., *et al.* (1988) and previous work done by these researchers at the Institute for Sensory Research at Syracuse University (Gescheider *et al.*, 1983; Gescheider *et al.*, 1985; Gescheider *et al.*, 1982; Labs *et al.*, 1978; Verrillo, 1963).

Representative absolute detection thresholds from Bolanowski, Gescheider, Verrillo, & Checkosky (1988) (see Fig. I-1) show thresholds that are constant (at 26 dB relative to 1 μm peak, i.e., 40 μm peak-to-peak) up to about 3 *Hz*, decreasing at a rate of about –5 dB/octave up to 30 *Hz* and, then, –12 dB/octave up to 300 *Hz*, after which threshold increases.

It is important to realize that the absolute sensitivity at a particular frequency as measured psychophysically is normally determined by the "channel" having the lowest threshold, this being a function of stimulus conditions such as body site, stimulator size, duration, skin-surface temperature, and static indentation. Also, because of the substantial overlapping of sensitivities among the four channels, at suprathreshold levels and with non-sinusoidal stimuli having broad

TABLE I-1. Summary of the properties of the four mechanoreceptors.

Channel	Pacinian	NP I	NP II	NP III
frequency response range (Hz) and shape	40 – 800 U-shaped, min @ 300	3 – 100 almost flat	15 – 400 U-shaped	<0.4 – >100 similar to NPI
threshold (re: 1 μm) & slope at low freq.	< −20 dB @ 300 Hz −12 dB / oct	28 dB @ 3 Hz −5 dB / oct	10 dB @ 300 Hz −6 dB / oct	28 dB @ 0.4 Hz almost flat
frequency over which threshold is lowest	> 30 Hz	3 – 30 Hz	none	< 3 Hz
sensory attribute	vibration	flutter	unknown	pressure[a]
temperature dependence	yes	yes	yes	yes
temporal summation	yes	no	yes	no
spatial summation	yes	no	unknown	no
physiological substrate	PC	RA (Meissner)	SA II	SA I

a. The perceptual quality associated with stimulation below 3 Hz is dependent upon stimulus intensity and stimulation site. When amplitudes are small and stimulation site can not be moved, as was true in Bolanowski *et al.* (1988) where absolute detection thresholds on thenar eminence were measured, a sense of pressure is perceived. When large amplitudes at very low frequencies are applied to the fingerpads, however, slow motions are perceived. (Footnote by the author.)

frequency spectra (e.g., pulse, ramp, noise), perceptual quality may be determined by the combined inputs from the four channels.

There is evidence that psychophysical detection threshold might be age-related. For example, Brammer *et al.* (1993) found that the threshold mediated by the Pacinian receptors at the fingertips decreased in sensitivity at an average rate of 2.6 dB per 10 years' increase in age, whereas there is little effect of age on SA and RA thresholds.

Intensity Discrimination

The dynamic range of the vibrotactile system is limited; it goes from detection threshold to roughly 55 dB above this threshold (i.e., 55 dB SL) beyond which vibrations become unpleasant or painful (Verrillo & Gescheider, 1992). The earliest study on intensity discrimination thresholds was probably done by Knudsen (1928). The right index fingertip was tested at 64, 128, 256, and 512 Hz with sinusoidal vibrations. It was found that the intensity JND (measured as 20 log [(A+ΔA) / A], where A=vibration amplitude and ΔA=ampiltude increment) was independent of

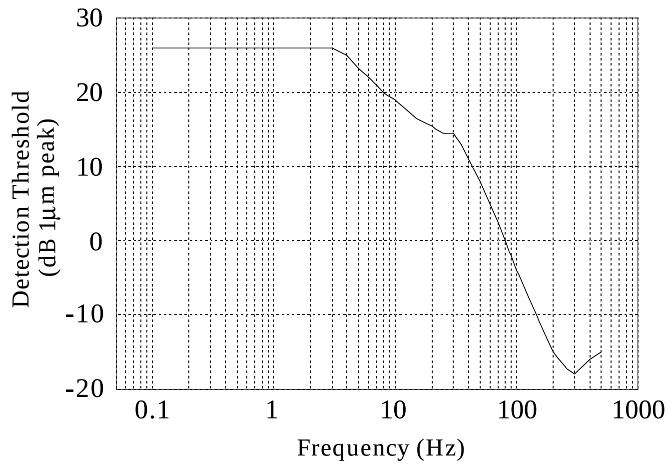

Figure I-1. Absolute detection thresholds for sinusoidal stimuli (from Bolanowski *et al.*, 1988).

frequency, decreased as intensity increased, and approached 0.4 dB when intensity was over 35-40 dB SL. In the fifties, researchers at the University of Virginia measured intensity discrimination on the ventral thorax (i.e., the chest) as part of the efforts to design the Vibratese language (Geldard, 1957). Intensity JNDs were found to decrease from 3.5 to 1.2 dB when the intensity of 60-*Hz* vibrations increased from 20 to 46 dB SL. In the seventies, Craig (Craig, 1972; Craig, 1974) studied vibrotactile difference thresholds for intensity in the absence and presence of background masking vibrations. The test stimulus was a 160 *Hz* vibration delivered to the right index finger. The masking stimulus was a 160 *Hz* vibration delivered to the right little finger. As expected, the lowest JND was obtained with no background vibration and the JND increased as the level of the masker increased from 2.0 to 20 μm peak to peak. Independent of the presence or level of the masker, the JND approached 2.0 dB when the reference intensity increased from 1 to 20 dB SL. In a more recent study (Gescheider, Bolanowski Jr., Verrillo, Arpajian, & Ryan, 1990), the thenar eminence was stimulated by a 25 or 250 *Hz* sinusoid, a narrow-band noise centered at 250 *Hz*, or a wideband noise. Of the three methods of stimulus presentation used, the continuous-pedestal method (i.e., an intensity increment imposed upon a continuous background 'pedestal' of vibration rather than on pedestals of brief duration) produced the lowest threshold. With this method, it was found that the JND decreased from 2.5 dB to 0.7 dB as stimulus intensity increased from 4 to 40 dB SL, independent of the power spectrum and frequency of the stimulus.

In summary, intensity JNDs decrease as intensity increases, are roughly independent of frequency, and range between 0.4 and 3.5 dB.

Frequency Discrimination

The frequency range over which the threshold for vibrotactile stimulation can be meaningfully measured is from DC to roughly 1 *kHz* (Verrillo & Gescheider, 1992). As Geldard pointed out (Geldard, 1957; Geldard, 1960), the task of measuring the frequency JND is not a simple one, due to the fact that perceived vibratory *pitch* depends on both the intensity and the frequency of the stimulation (more so than auditory pitch). For example, when vibratory frequency is fixed and a subject's attention is directed at pitch, a decrease (or increase) in pitch is perceived when the intensity is increased (or decreased). Thus, control for differences in subjective intensity (i.e., vibratory loudness) and for contaminating transients at onset and offset points of the stimulus envelope is crucial for *pitch* JND measurements. In this review, we use the term *frequency JND* for results obtained without equalizing vibratory loudness, and *pitch JND* for measurements made with equal-loudness vibratory stimuli.

The results on frequency discrimination JNDs are mixed. Knudsen (1928) obtained an average frequency JND (in terms of $\Delta f/f$) of 15 to 30% using 34 dB SL vibrations at 64 – 512 *Hz* delivered to the index fingertip (duration of stimuli was not documented). Mowbray & Gebhard (1957) found that the frequency JND increased from 2 to 8% when the repetition rate of intermittent mechanical pulses increased from 1 to 320 *Hz*. Pulse duration increased from 1.5 *msec* at 320 *Hz* to 7.5 *msec* at 1 *Hz*, and intensity of stimulation varied from 17 to 26 dB SL. Note that because the subjects felt vibrations through a rod between two fingers, these numbers may be lower than those from a standard one-finger experiment. The first author to use stimuli of equal subjective intensity for frequency discrimination was probably Goff (1967). Sinusoidal 1-*sec* long vibrations were delivered to the index finger. When frequency increased from 25 to 200 Hz, the pitch JND (in terms of $\Delta f/f$) increased from 18 to 36% for stimuli at 20 dB SL and from 31 to 55% for stimuli at 35 dB SL (relative to absolute detection threshold at 100 *Hz*). Rothenberg, Verrillo, Zahorian, Brachman, & Bolanowski (1977) explored the possibility of displaying the fundamental frequency of speech to the skin through frequency-varying (warbled) stimulus patterns. The volar forearm between palm and wrist was tested with four types of 1-*sec* long stimuli: constant-frequency sinusoids and pulse trains (equal subjective magnitude at 14 dB SL), and sinusoids and pulses with time-varying frequencies (at 20 dB SL). Over the frequency range of 10 to 300 Hz, the pitch JND increased from 15 to 25% for constant-frequency sinusoids, and from 10 to 35% for constant-frequency pulses. However, warble-tone stimuli improved discrimination at higher frequencies: the pitch JND decreased from 40 to 9% for warble-tones, and from 50 to 20% for warble-pulses. Another study (Franzen & Nordmark, 1975) reported a very low pitch JND of 3% at 30 dB SL. However, the methodology was non-standard and it was questionable if the authors had measured the uncertainty about the JND or the JND itself (see Rothenberg *et al.*, 1977, p.1004). Formby, Morgan, Forrest, & Raney (1992) measured vibrotactile frequency resolution on the thenar eminence using 250 *Hz*, 800 *ms* (with 10 *ms* rise / fall ramps), 100% sinusoidally amplitude modulated carriers. The overall level of each stimulus was randomized over a range of ±5 *dB* around a mean level of about 25 *dB* SL. A 2AFC adaptive procedure with 200 *ms* interstimulus interval was used. They found Weber fractions of 30 to 40% for modulation frequencies of 5 to 60 *Hz*, and much higher Weber fractions of 64 and 76% for modulation frequencies of 80 and 100 *Hz*.

In summary, the results from several studies (Knudsen, 1928; Goff, 1967; Rothenberg *et al.*, 1977; Formby *et al.*, 1992) with constant-frequency stimuli are consistent and indicate relatively poor frequency / pitch JNDs (10 to 76%) that increase with frequency over a range of 5 to 512 Hz. The study by Rothenberg (Rothenberg *et al.*, 1977) showed that when frequency-varying stimuli were used, the pitch JND decreased with frequency. These studies also indicated that the JND increased when intensity cues were eliminated by careful matching of the subjective magnitude of the frequencies being discriminated. Other studies cited above were less consistent with this picture, presumably due to differences in experimental methodology.

Temporal Resolution

Using 60-*Hz* vibrations on the ventral thorax, Geldard (1957) found that duration JNDs increased monotonically (and almost linearly) from 50 to 150 *msec* when duration increased from 0.1 to 2.0 sec. It was estimated that there were roughly 25 JNDs within the duration range tested.

Gescheider (1966) measured the time difference (Δt) between the onset of two clicks necessary for non-fused perception (defined as two temporally separated sensations, or when a rough rather than a smooth sensation was perceived). Measurements were obtained using the method of limits on either bilateral index fingertips, ipsilateral ring and index fingertips, or a single area on the index fingertip. The intensity difference between the first and the delayed stimuli ($\Delta A = A_{delayed} - A_{first}$) varied from –15 to 20 dB, with the more intense stimulus kept at 35 dB SL. Mean Δt threshold *vs.* ΔA curves for the three stimulation sites tested were U-shaped with minimal thresholds occurring at ΔA=5 dB. This minimum Δt was 12.5 *msec* for bilateral index fingertips, and 10.0 *msec* for ipsilateral ring and index fingertips, or single area on the index fingertip. (Similarly determined auditory resolution was around 1.6–1.8 *msec*.) The tactile threshold of 10.0 *msec* was very close to the response duration of the vibrator to a 1-*msec* square wave. It is unclear, therefore, whether the minimum threshold was limited by the experimental apparatus. In Gescheider (1967), two additional experiments were conducted with ipsilateral ring and index fingertips stimulation. In the first experiment, Δt decreased from 50 *msec* to 10 *msec* when $A_{delayed} = A_{first}$ varied from 10 to 35 dB SL. In the second, Δt decreased monotonically from 50 *msec* to 22 *msec* when $A_{delayed}$ increased from 10 to 35 dB SL and A_{first} was fixed at 20 dB SL. When $A_{delayed}$ was fixed at 20 dB SL and A_{first} increased from 10 to 35 dB SL, the Δt vs. A_{first} curve was U-shaped with a minimum of 30 *msec* at A_{first}=15-20 dB SL. These results were explained by hypothesizing suppressive effects of the first stimulus on the neural response produced by the delayed stimulus.

Van Doren, Gescheider, & Verrillo (1990) used a 2AFC gap-detection paradigm to measure tactile temporal resolution on the right thenar eminence as a function of age (8–75 yrs old). The stimulus contained either two 350-*msec* bursts separated by a gap, or a continuous burst with the same total duration. The bursts were either 256-*Hz* sinusoidal vibrations or bandpassed (250–500 *Hz*) noise. In any experimental run, the duration of the gap was fixed, and the threshold was measured in terms of the lowest stimulus amplitude necessary to detect the gap using a tracking paradigm. The data from noise stimuli agreed well with the data from clicks obtained by Gescheider (1967). Sinusoidal thresholds (in dB SL) were lower than noise thresholds, especially at shorter gaps. The threshold for detecting short gaps increased with age for noise stimuli, but not for sinusoidal stimuli. It was argued that the effects of age on gap detection may be due to multiple processes.

A Vibrotactile Communication System: The Vibratese Language

In the fifties at the University of Virginia, a vibratory communication system was developed and tested on three subjects (Geldard, 1957). The system consisted of five calibrated vibrators placed at the four corners and the center of a rectangle on the chest. Three intensities (*soft*, *medium*, and *loud* within 20 to 400 μm), three durations (0.1, 0.3, and 0.5 sec), and the five loci, all absolutely identifiable, formed a 45-element system. The frequency of vibrations was fixed at 60 *Hz*. Fig. I-2 illustrates the coding of the so-called *Vibratese language* which was designed to transmit single letters and digits as well as the most common English words. Note that locus, the most *distinctive* cue provided by the system, was used to encode the five vowels at the shortest duration and highest intensity. Long durations belonged to numerosity. Frequently occurring letters were assigned to the shortest duration in consideration of communication speed. The five elements corresponding to the medium intensity and longest duration were not used.

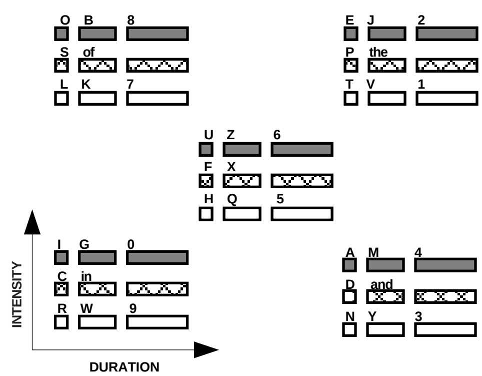

Figure I-2. Coding of the Vibratese language. Each group of nine symbols belongs to a single vibrator that varies in intensity (3 steps) and duration (3 steps). The five vibrators display all letters, all numerals, and the most frequently encountered short words. (From Geldard, 1957, Fig. 3)

The sending system was built around a typewriter and the maximum sending speed was estimated to be 67 words per minute by assuming five-letter words as the standard. Subjects learned the code for single-letter presentation in about 12 *hours*. The best subject reached a receiving plateau rate of 38 words per minute (words and sentences).

I-1.2 Kinesthetic Senses

The term kinesthesia refers to our awareness of body postures, movements, and muscle tensions. Only studies on the perception of joint positions and motions induced by external sources are reviewed here. The stimuli used in these studies are usually low-frequency signals.

The physiological mechanisms underlying kinesthetic sensing have been the topic of controversy since the turn of the century. It is now generally accepted that muscle receptors are the most likely candidates for kinesthetic detectors. The role of tactile receptors (i.e., the detection of skin stretch) is not clear and is thought to signal joint movement but perhaps not joint position. Joint receptors are found to be responsive only when the joint is near the extremes of flexion or extension. See Clark & Horch (1986) for an excellent general review of the literature on kinesthesia.

Passive Movement-Detection Threshold

Most studies on perception of passive movements involve rotating a joint smoothly at a constant velocity with minimal vibration and without visual feedback. Subjects usually have lower thresholds (i.e., better acuity) for detecting a joint movement than for identifying the direction of motion. Reported detection threshold values range from 0.20 to 6.10°, depending on the joints tested and the rate of rotation used. When detection of angular rotation is considered, proximal joints like the hip and shoulder show a greater sensitivity to movement than distal joints like those in the fingers (Clark & Horch, 1986). However, if performance is defined in terms of linear displacements of the endpoint (i.e., the fingertip for the arm), the distal joints are superior to the proximal joints (Hall & McCloskey, 1983).

The detection of passive joint movement is dependent upon the rate of rotation. Excursions that go unnoticed at one speed may become readily detectable at a faster speed. Clark, Burgess, & Chapin (1986) demonstrated that the PIP (proximal interphalangeal) and MCP (metacarpal interphalangeal) joints of the human index finger differ in their ability to detect passive joint movements. With the PIP joint, a subject’s ability to detect a small change in joint position (e.g., 5°) was impaired when the rate of rotation was progressively reduced from 128 to $2\ {}^{\circ}/min$. With the MCP joint, however, subjects could detect small (2.5°) flexion-extension displacements of the joint with no appreciable decrement in performance from almost 100% accuracy when the rate of joint rotation decreased from 128 to $1°/min$. Therefore, it was suggested that humans have a *static-position sense* with the MCP joints, but only a *movement sense* with the PIP joints. In general, movement has a more vivid character than position.

Limb Position / Movement Discrimination

In a typical limb-position matching experiment, the subject is asked to match the position of the reference limb with the other limb. The reference limb is either self- or passively-positioned and either self- or passively-maintained. Results are characterized by accuracy (i.e., offset of the mean of the errors), and precision or variability (i.e., standard deviation around the mean of the errors). Studies show that self-positioned limbs are matched more accurately than passively-positioned ones regardless of whether the reference limb is self- or passively-maintained. There is a tendency for precision to be better at the most flexed and extended joint positions than at the middle of the joint position range. There is also a tendency for accuracy to be best at the middle of the test range and biased towards the middle at other joint positions (see Clark & Horch, 1986). Jones & Hunter (1992a) measured differential thresholds for limb movement by asking subjects to compare the standard deviation (SD) of two 6-*sec* 15-*Hz* bandlimited Gaussian displacement perturbations delivered simultaneously to the two arms anchored at the elbows. They found a Weber fraction of 8%, which meant that subjects could resolve a difference as small as 5 μm between two perturbations when the reference SD was set at 50 μm. Jones & Hunter (1992b) also report a similar Weber fraction of 8% for position discrimination.

We have found that the differential threshold for the PIP and MCP joint angles is around 2.5° using active finger motions (unpublished results). The threshold is 2.0° for the wrist and elbow joints, and decreases to 0.8° for the shoulder joint (Tan, Srinivasan, Eberman & Cheng, 1994). As in the case of joint movement detection, proximal joints are more sensitive to position changes than distal ones when performance is defined in terms of joint-angle resolution. Proximal joints are less sensitive when displacements of the endpoint are considered.

I-1.3 Devices that Stimulate the Kinesthetic Senses

As mentioned earlier, most tactile communication devices employ vibrotactile stimulation characterized by high-frequency low-amplitude signals. The only two devices of which we are aware that stimulate the kinesthetic as well as the tactile components of the tactual sensory system are reviewed here. One of them was developed by Bliss (1961) at the Massachusetts Institute of Technology. Bliss's Ph.D. thesis was concerned with the development of a tactual communication system via an "inverse typewriter". It touched upon many important issues that are encountered in this thesis work. A detailed review of his thesis is provided. The other device, called OMAR, was developed recently by researchers at Gallaudet University (Eberhardt *et al.*, 1994). A brief review of the limited information currently published on OMAR will also be provided.

Review of Bliss (1961)

Four basic psychophysical experiments were conducted to guide the development of Bliss's stimulator. They were amplitude discrimination, direction identification, finger location identification, and pattern recognition with visual and tactual senses. The first three are reviewed here.

Discrimination of Passive Finger Movement Amplitudes

The stimuli were generated by sending a position-pulse to a servo motor with potentiometer feedback. The length of the linkage interfacing the servo motor and the finger was unspecified. A two-interval discrimination paradigm was used. The difference limen (DL) was defined as the movement amplitude difference between a standard stimulus (ST) and a comparison stimulus that was noticed 50% of the time. Weber fraction was computed as DL / ST. For STs of 0.70 and 0.57 *mm*[1] (with two subjects per ST, unspecified number of trials, pulse durations of 68.8 and 110 *msec*, respectively, rise time of 15 *msec*, and up-down finger motions with the unspecified finger extended), the average Weber fraction was found to be around 8% (Exps.1–4, p. 40–41, Bliss, 1961). For an ST of 0.70 *mm*, one subject was tested with pulse durations of 50, 90, and 200 msec, and the resultant Weber fractions were 5.9, 5.3, and 5.9%, respectively (Exps. 5–7, p.40–41, Bliss,

1. All units were converted to metric units for consistency.

1961). This one subject was doing consistently better in the second set of experiments than under comparable conditions in the first set of experiments. In a third set of experiments (Exps. 8–10, p.40–41, Bliss, 1961), the same single subject was tested at an ST of 0.74 *mm* with three different finger postures (with pulse duration of 95 *msec*) and the Weber fraction was found to be 4.2 and 4.6% with up-down motions with the knuckle (I assume that Bliss meant the PIP joint) bent and the unspecified finger extended, respectively, and 8.1% for sidewise motions. Once again, this subject's performance improved by another 2% under conditions comparable to those tested in the first two sets of experiments.

To summarize, the Weber fraction was 4 to 8% for ST of 0.57 to 0.74 *mm*, pulse duration of 50 to 200 *msec*, and up-down as well as sidewise finger motions. More subjects need to be tested with systematically varied parameters in order to establish these results.

With a very sketchy description, the author reported a Weber fraction of 18% for pulse duration with a reference duration of 160 *msec*. The author also concluded from another briefly described experiment that the subject seemed to be able to *"accurately detect a change in the area or energy of the pulse, but he can not discriminate between a change in pulse height and a change in pulse duration."* This is an interesting result that warrants further investigation.

IT and IT rate for Passive Finger Movement Directions

A device similar to a typewriter key powered by three mutually perpendicular solenoids was used to generate motions of approximately 4.7 *mm* in six directions (see Fig. I-3). Two sets of experiments were conducted with the right index finger. The first set of experiments employed a one-interval absolute identification paradigm (unclear if feedback was given) with single 70 *msec* movement pulses. Information transfer (IT) was found to be 1.58 *bits* (46 trials, no errors) when directions 1, 2 and 3 were used, 1.57 *bits* (96 trials) when directions 1, 2, 5 and 6 were used, 1.43 *bits* (284 trials) when directions 1, 2, 3, 4 and 5 were used, and 1.54 *bits* (279 trials) when all six directions were used (number of subjects unknown in these experiments). Therefore, a maximum IT of 1.58 *bits* could be achieved when the movement directions were orthogonal to each other in a 3D space.

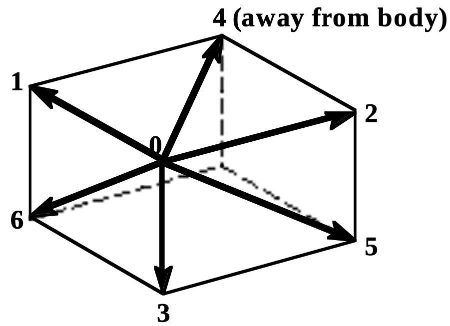

Figure I-3. The six directions of finger movement studied by Bliss. "0" is the rest position.

In the second set of experiments, two position pulses were delivered to the right index finger in rapid succession. Using all six directions, the IT rate was 3.4 *bits/sec* at a presentation rate of 2.2 *movements/sec*, and 3.52 *bits/sec* at a presentation rate of 3.7 *movements/sec*. Three higher presentation rates were tested, but data in terms of IT rate were not given.

In another experiment, a device capable of moving in the ±x, ±y and ±z directions was used to deliver a sequence of three movements at a rate of 2.8 *movements/sec*. The resultant IT rate was 4.7 *bits/sec* (6 untrained subjects and a total of 180 trials) suggesting that a higher IT rate could be achieved by moving the fingers in mutually orthogonal directions.

Identification of Finger Locations

In this experiment, pairs of fingers (the index, middle, and fourth fingers of each hand) were moved upwards for approximately 3.2 *mm* with a duration of 10 *msec*. Two subjects were asked to identify the pair of fingers being moved and each received 120 presentations. The data were presented in a 6x6 confusion matrix. It was not clear how Bliss converted the subject's response in terms of finger pairs to entries in the confusion matrix in terms of single finger locations. Nevertheless, Bliss concluded that *"(1) Most errors in finger localization result from confusion between adjacent fingers on the same hand; and (2) There were more errors involving the middle finger of each hand than any of the other four fingers used in the experiment."* (Bliss, 1961, p. 52)

The Air-Driven Finger Stimulator and Results of the Typewriter Presentation

Based on the above results, an air-driven "reverse-typewriter" was developed. This display was extremely clever; a picture of it can be found on p. 73 of Bliss (1961). Basically, the stimulator consisted of eight finger rests arranged in two groups. The user could place the two hands on these finger rests in a manner similar to typing. Each finger rest was capable of moving in ±x, ±y and ±z directions. Since each axis could be in the +, –, or neutral position, there were a total of 27 (3×3×3) states per finger rest. It was not clear how much displacement was achievable along any given axis, although it was mentioned that the amplitude of motion began to decrease rapidly at speeds greater than 15 *words/min*.

Several types of presentations were tried with the pneumatic finger stimulator. The type most relevant to this thesis is the *typewriter presentation*. In this presentation, the fingers were moved in a way similar to the active motions of a typist. For example, finger movements toward the body indicated the characters corresponding to the bottom row characters on a typewriter. Some modifications were used in order to incorporate all alphanumeric codes. For instance, lower and upper cases were indicated by the simultaneous movement of three fingers, etc.

In one set of experiments, 42 random triplets composed of the six letters *e*, *t*, *n*, *a*, *o* and *i* were presented to eight subjects. The average IT was 1.75 *bits/letter* out of a maximum possible 2.58 *bits/letter*. In another experiment, 30 symbols (the alphabet, comma, period, space, and upper case) were presented in random order with equal probability to one subject (with less than 15 hours of practice). Six sequences of 130 symbols each were delivered at a rate of 0.5 to 1.5 *letters/sec*. The subject responded verbally by naming the symbols as they were received. The IT rate, computed as the product of percent-correct scores, presentation rate (*letters/sec*) and information per symbol (4.91 *bits/letter*), reached a maximum of 4.5 *bits/sec* at a presentation rate of 1.32 *letters/sec*. Bliss argued that a higher IT rate could be achieved if the subject received more training, if more alternatives per symbol were used, and if the codes for different symbols were more evenly distributed among the fingers tested. The bandwidth of the device itself may have also been a limiting factor. Bliss commented that the typewriter presentation was easy to learn, especially if the subject had a previous knowledge of typing; but no comparison of training data from typists and non-typists was provided.

Review of Eberhardt et al. (1994)

OMAR was motivated by the desire to use kinesthetic as well as vibrotactile stimulation to present speech information as a supplement to lipreading. Its actuator was based on the head-positioning motor of a Micropolis hard-disk drive. A linear potentiometer was used as a position sensor, and an adjustable dashpot was used to assure system stability as the loading condition changed abruptly (e.g., the finger left the device briefly). Although no force sensor was used, the error gain, hence the stiffness of the system, was programmable. Sufficiently bandlimited low-frequency high-amplitude movements were closed-loop controlled. According to the authors (Eberhardt *et al.*, 1994), the system operated open-loop at vibration frequencies "due to limited dynamic range of the position potentiometer and drive circuit." Frequency responses for movements (i.e., 0.5 to 20 *Hz*) and for vibration (i.e., at 100, 200, 400, and 800 *Hz*) at several signals levels were presented. From the magnitude-gain plot for movements, the system appeared to be nonlinear. The –3 dB bandwidth at low frequencies ranged from about 19 to 10 *Hz* for nominal amplitudes from 10 to 40 *mm*. From the amplitude plot for vibrations (measured with an accelerometer), the magnitude gains (assuming 0 dB gain at 0.5 *Hz*) were approximately –36 dB at 100 *Hz*, –50 dB at 200 *Hz*, –56 dB at 400 *Hz*, and –58 dB at 800 *Hz*. As an example of how OMAR was utilized in psychophysical experiments, the psychometric function for vibration onset asynchrony (VOA) was measured. Subjects were asked to judge the asynchrony of a vibration and a movement (maximum displacement: 28.7 *mm*, rise time: unclear). The VOA time for judging that vibration started before movement was between –38 to –75 ms (a negative sign means vibration leads movement). Additional psychophysical studies are being conducted with the OMAR system. For example, Craig and Rinker (informal presentation at the Tactile Research Group meeting in Los Angeles, Nov. 9, 1995) described frequency and amplitude discrimination experiments with one or two fingers (of the same or different hands).

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