Spatial Factors in Vibrotactile Pattern Perception

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Abstract
The spatial acuity of the skin for pressure stimuli has been explored extensively, but there have been few attempts to study spatial resolution for vibratory stimuli of the type used in tactile aids for sensory disability or to augment communication. Because vibrotactile spatial acuity has never been empirically determined at such sites, pattern perception with these devices might be poorer than it could be if the stimulus parameters that optimize localization were known. Vibrotactile localization was measured on forearm and abdominal sites used by wearable tactile communication aids. Surprisingly, stimulus frequency did not affect localization on the arm, tested on 8 Os for a given spatial arrangement; both on the arm and trunk (tested with 8 Os), fewer than half of the sites were uniquely identified. Because tactile aids should be usable throughout a person’s life span, especially in the later years, older persons will also be tested in these studies of spatial vibrotactile pattern perception.

1. Introduction
Tactile devices to augment communication are becoming more common in everyday life, especially to serve as prostheses for sensory disability or. Such systems include speechreading aids used by deaf persons (e.g., the Tactaid, worn on the forearm or chest), reading machines for blind persons (the Optacon, used on the fingertip), spatial orientation systems used by pilots or astronauts (the Tactile Situation Awareness System, on the trunk of the body), and even vibrating pagers and cell phones. In every case, vibrotactile spatial acuity has never been empirically determined at the application site, so pattern perception might be poorer than it could be if the parameters that might optimize localization were known. We are currently exploring localization ability and vibrotactile spatial acuity at a number of these. Because it is likely that stimulus parameters such as vibration frequency might affect localization at a site, these are also being varied. The two sites we have examined initially are the trunk of the body and the forearm. In this paper we will describe localization ability and information transfer on these sites. Because tactile aids should be usable throughout a person’s life span, older persons are also being tested in these studies of spatial vibrotactile pattern perception. The long-term objective of this research program is to understand better both the sensory and perceptual processes that underlie rapid and accurate performance with cutaneous communication systems.

1.1. History
Spatial acuity has been used as a measure of tactile sensitivity for over 150 years. Weber’s classic 1826 work [62] describes attempts to measure tactile acuity on a number of body sites. The two primary methods used then (and now- e.g., [63]) are to measure the minimal separation required to discriminate one versus two points touching the skin, the 2-point threshold, and error of localization, which is the accuracy with which the location of a touch can be identified. Over the years, it has become clear that methodology plays a large role in determining the threshold levels obtained [6], [18], [40]. Johnson [34] and Stevens [53, 54] describe improvements in the methodology and the devices used for testing that reduce subjective biases and more appropriately measure the minimum distance that can be perceived between two durative points touching the skin. Nevertheless, serious problems remain. Tawney [55] and, then one hundred
years later, Johnson [35], argued that the two-point threshold cannot measure tactile spatial resolution because spurious cues such as intensiveness differences are inherent in the presentation of single versus paired points. Even a pin-prick has a spatial quality, and produces a sensation of tactile “extensity” ([55] p. 592). The traditionally-obtained thresholds therefore may only represent “the categorical perception of a distance at which separation between two points is no longer ambiguous” [64].

The history of the study of tactile acuity, rarely has included the minimum separation on the skin required to resolve vibratory stimuli, perhaps because it is so difficult. Kirman [37] elaborated on a number of demonstrations of the apparent inability to resolve simultaneous vibrotactile stimuli, as did Craig [16]. Yet, the simple question - “How close together can we place vibrating tactors before their loci become indistinguishable?” - is still often raised by designers of wearable multi-tactor arrays. Typically the two-point limens for touch are cited to support a particular spatial design for vibrotactile arrays. Yet, one must assume that vibratory stimulation will extend well beyond the limits imposed by contactor boundaries. Analyses of the waves propagated on and in the skin from vibratory stimuli like those shown in Figure 1 by Franke [21] and Keidel [36] suggest a number of parameters that can influence the skin’s resolution for vibratory stimuli. A static surround may damp the spread of surface waves [26], but not those passing through deeper tissues, where many of the cutaneous receptors lie, as shown (for hairy skin) in Figure 2. The velocity of traveling waves in the human skin not only depends on the viscoelastic properties of the skin itself, but also on factors as varied as vibration frequency, skin temperature, and whether underlying tissue is bone, fat, muscle, or a combination.

Clues to the relevant variables in any study of vibrotactile spatial acuity can be found in studies in which two (or more) stimuli were used to examine other aspects of tactile processing. Profound interactions are revealed among stimuli, particularly when presented close together in space and in time [37]. For example, Békésy [2, 3] described increases and decreases in apparent location and perceived magnitude of the stimuli when two vibrating points are brought close together spatially and temporally (within cm and ms). Geldard, in his studies of sensory saltation [24, 25] demonstrated a number of ways in which the apparent locations of tactile, visual, and auditory stimuli shift with larger temporal disparities. Similarly, Gilson [29], Sherrick [51], and others have examined the “masking” interactions that occur when two vibratory stimuli are presented close together in space and/or time, finding that the closer the two are to one another (on either dimension), the more the sensation magnitude of the test stimulus will be reduced. Furthermore, in studies of tactile masking, where the accuracy of identification of complex two-dimensional patterns is reduced in the presence of a masking stimulus [12, 14], error analysis shows subtle spatial interactions between pattern and mask [11, 15]. Similarly, Craig [17] demonstrated that the ability to localize patterns on an array was influenced by the presence of preceding stimuli, especially when test and target were at two different locations. Even physiological data indicate varying degrees of interaction between stimulated loci [23, 31]. These findings of simple and complex vibrotactile spatial effects warrant further exploration of the bases of the interactions that could affect the encoding of information from tactile communication aids and devices.
There are only a few studies of tactile resolution in which the ability to localize vibrotactile stimuli has been specifically examined (notably, [58]). In attempting to determine the appropriate spacing for tactors in the Tactile Vision Substitution System, Eskildsen [19], explored simultaneous and successive two-point thresholds on the lateral back near the scapula for 2 sec 60 pps stimuli, finding that threshold could be as small as 11 mm for pairs of 1 mm contactors (Weinstein’s [63] static two-point thresholds were c. 4 cm). Rogers [49] examined spatial resolution on the fingertip, with two constantly-vibrating tactors. For frequencies of 10 and 250 Hz, resolution was a function of separation with poorest performance at 2 mm. Sherrick, Cholewiak, and Collins [52] used carefully-controlled 25 or 250 Hz stimuli to appeal to high- and low-frequency sensitive cutaneous channels. Observers indicated the location of a burst of vibration on the hypothenar eminence of the palm (the edge opposite the thumb). Accuracy was generally above 75%, with low-frequency stimuli only slightly better localized. The absence of parametric vibrotactile spatial acuity data needs to be addressed directly, in order for tactile communication systems to be used efficiently.

1.2. Pattern perception & spatial localization

The history of device design illustrates that the resolution of displays has rarely been determined empirically. Rather, designers have resorted to the data published in Weinstein’s oft-cited 1968 paper that describes error of localization and 2-point threshold obtained over many body site. As an example, Bliss [4] carefully analyzed the spatial resolution of cameras used to record text for direct-translation aids for blind persons, relating the resolution of the device to the spatial frequency bandwidth of the images to be processed. However, to determine the resolution of the vibrotactile output device, he used Weinstein’s static two-point data as a measure of the skin’s acuity. As a guide to the development of vibrotactile patterns and devices, these measures, obtained with static patterns, are being inappropriately generalized to vibratory stimuli. The relationship between two-point threshold and performance on durative patterns such as Braille cells seems more intuitive. Indeed, Stevens [54] argues that the reduction in static tactile acuity with age they measured has serious consequences for blind persons trying to read Braille characters. It is likely, however, that the active movement of the fingers over the cells in normal Braille reading adds a level of richness to the tactile pattern that may compensate for the inherent mismatch between static stimulus and aging receptive systems. In contrast, vibrotactile arrays in devices like the Tactaid, Optacon, TVSS, or TSAS, described earlier, cannot be actively explored. These have tactor arrays designed for passive reception. In none of these arrays has there been a quantitative measure of their ability to accurately present vibrotactile patterns that have spatial characteristics matching those of the application site.

The accuracy with which persons can process tactile patterns, given appropriate temporal factors, ultimately comes down to an interplay between the spatial acuity of the skin and the spatial resolution of the patterns and display. Some have argued that the poorer performance often seen with tactile patterns is a natural consequence of the inferior acuity of the skin, at least in contrast to the visual system [41, 42]. Recent tactile data have shown differences in pattern identification performance between old and younger subjects that appear to be directly related to poorer spatial resolution in the older group [9, 10].

1.3. Aging & spatial localization

We will also be examining vibrotactile pattern processing in elderly persons to compare their performance against that from the younger population. This exploration into aging is warranted for several reasons. Hearing acuity decreases rapidly after the age of 60 irrespective of specific otological disease [20], while 88% of visually-disabled persons are over the age of 60 [28]. Consequently, understanding the capabilities of the sense of touch in the older individual has great importance, since it may often be the only alternative system available to supplement remaining sensibility. Furthermore the study of tactile pattern processing in this group, because of the known changes in the peripheral nervous system, should help us understand the mechanisms involved in tactile perception, and show how these findings might be incorporated into better devices for sensory substitution or augmentation.

Basic research on processing of tactile stimuli has demonstrated significant changes with age revealed when a single touch or a burst of vibration is presented to the skin [53, 59, 60]. Typically these studies have been concerned with measuring tactile or vibrotactile thresholds [22, 46, 80]. In most cases there is a decline in the capacity [30]: thresholds increase, or discriminative capabilities are poorer, in older individuals. A few notable studies have found similar declines in performance when the effects of aging are examined in complex measures of tactile pattern processing, such as haptic or form exploration [1, 13, 38], spatial acuity [53]), or temporal processing [57]. The underlying cause of the progressive loss has usually been attributed to physiological changes in the skin itself [53, 59] or neurological factors [39, 43, 61]. The functional decline in tactile perceptual skills also parallels age-related anatomical and morphological changes in the skin and its receptors. In aging skin, the size, shape, and number of cells in the upper layers become quite variable and glands
often atrophy or become inactive [44]. Dramatic age-related alterations in some mechanical properties of the skin such as compliance, surprisingly, do not appear to be tied to reductions in tactile sensitivity [65]. Changes with aging in the receptors themselves have also been fairly well documented. In general, while the number decreases, structural complexity increases. For example, there are one-third as many Meissner corpuscles in some body sites in 70-year-old individuals as in 20-year-old persons [50]. In addition, there are fewer Pacinian corpuscles, and those that remain undergo dramatic distortions in shape and size, while Merkel’s disks and free nerve endings undergo less-obvious changes with age [7]. Because these structures and others have been related to different aspects of tactile sensitivity [5, 33], a correlation would be expected between these changes and variations in tactile acuity. Although tactile pattern perception requires a combination of both spatial and temporal processing abilities, we are primarily studying spatial processing abilities to provide a measure of the change in this sensory capacity in older subjects relative to a younger population.

But how well does the skin appreciate spatial stimuli? We are probably familiar with illustrations like the next one – showing the considerable variation in sensitivity over the surface of the body for simple touches, or pressure stimuli (from Weinstein [63]).

![Image of pressure threshold variation over the body](image)

Figure 3. Variation in pressure threshold over the body (From Weinstein [63]).

Similar pictures have emerged when pairs of such points were used, but, as discussed earlier, there is are serious questions regarding the validity of these data. Nevertheless, there is little question that tactile sensitivity varies considerably over the body’s surface, whether measured by one or two touches. But what about vibration? As we saw earlier, the patterns of activity resulting from vibration and in the skin can be quite complex and widespread, as shown in Figure 1. Such a pattern can also result from more natural stimuli such as rubbing or stroking of the skin, although stretch components are also introduced.

So what happens when we look at the skin’s sensitivity to vibration? Observers judged stimuli that varied in vibratory frequency over the normal range of sensitivity of the skin – from about 20 to about 300 Hz, of varying intensity. They indicated when they just felt the stimulus. When we compare the results on the palm of the hand versus the arm (smooth versus hairy skin), we have seen impressive differences (Figure 4). Hairy skin is less-sensitive over the whole range. A few additional data points are shown in the graph from a single observer in my lab. These are thresholds taken on the costovertebral angle of the back. Depending on where one places the stimulator, within a range of a few cm, a high-frequency dip can be recorded – or not! These data suggest the presence of different underlying physiological systems – receptor channels that differ across body sites, within body sites, and over the age span.

Physiological data certainly support these notions – 40 years ago, Sato, von Bekesy, and others indicated that at least one component of these curves, the high-frequency dip – reflected the operation of one known receptor, the Pacinian Corpuscle – which is found to be sparsely distributed in hairy skin (Figure 5). Anatomical exploration has shown even more structures that could be involved in tactile sensitivity, and, more recently, these
have been related to specific perceptual experiences when
the glabrous skin of the hand was stimulated [48].

Figure 6. Properties of 2 superficial glabrous skin
receptor structures (after Vallbo [56]).

Other research has shown that in the human hand, the
superficial receptor structures (Figure 6) have extremely
high densities in the fingertip skin, much greater than that
of the deeper structures. Nevertheless, recall that the
most dramatic variations in sensitivity were in the high
frequency ranges where the Pacinian determines
threshold. Remarkably, given the extraordinary
sensitivity of this receptor system (less than 1µ at 250
Hz), it is the deepest-lying of all of the structures. When
we try to decide which of these subserves spatial pattern
processing, single unit data suggest significant differences
in their ability to resolve spatial detail when presented
with patterns even as simple as Braille cells.

2. Spatial localization on linear arrays

How does vibratory spatial sensitivity vary over the
surface of the body? There are no data in the literature
like those we saw for the two-point thresholds. We have
collected some data that address the accuracy of
resolution of spatial vibrotactile stimuli on two body sites:
the forearm and the trunk of the body. In the first case,
eight subjects were asked to identify 7 locations of 150-
msec bursts of 100 Hz or 250 Hz vibration on a linear
array, equated in perceived intensity. Stimulus frequency
was varied in order to appeal to different underlying
receptor systems, since they also have been reported to
have different spatial sensitivities. Examining the
distributions of correct responses and errors to each site in
the first session of 5 blocks of 70 identification trials, (in
Figure 7), we see that when sites are 25 mm apart,
accuracy is

Figure 7. Localization of sites on a 7-tactor linear array
on the forearm; 25 mm separation, 100 Hz (upper
graph) and 250 Hz (lower).

quite poor for this task, particularly in the mid-range of
loci. The higher accuracy at the ends of the range has a
number of sources we could discuss (specifically related
to “anchor points” [6]). Remarkably there is no
meaningful difference between the functions obtained for
the two frequencies.

What would happen if we expanded the separation
and used fewer tactors (since the forearm has a fixed
length)? The next sets of data were taken from one of our
studies in which the 100-Hz stimuli were presented at 4
sites separated by 50 mm to younger (college-age) and

Figure 8. Localization of sites on a 4-tactor linear array
on the forearm by students (left) and seniors (right):
50 mm separation, 100 Hz.

older (60+ yrs) subjects. The results plotted as a
confusion matrix in Figure 8, indicate that students were
more precise, making fewer errors particularly for sites
more than 50 mm away from the target. Although
performance was quite good overall, the students were
particularly accurate in the interior sites. These studies
are continuing, and will be expanded to other body sites.
Finally, we examined the accuracy with which spatial vibrotactile stimuli are resolved on the trunk of the body. In this case, seven subjects were asked to identify the locations of 150-msec bursts of 250-Hz vibration presented on a belt of 12 vibrators spaced at equal intervals around the lower abdomen, at a level just above the umbilicus. Here, trained observers responded on a 3-dimensional cylindrical keyboard, as shown in Figure 9. They were instructed to encode the stimuli (and key positions) as though they represented hours on the clock face, with 12 o’clock located at the navel and 6 o’clock at the spine. The data were collapsed over two sessions of 300 trials, and responses plotted as before, as a function of the stimulus location, in Figure 10. Again, average performance was very good, but note that optimal identification occurred at what might be defined as “anchor points” at the front (12 o’clock) and rear (6 o’clock) of the trunk – the navel and spine.

Finally, despite the apparent accuracy of identification Figure 9. Participant working with the 12-site 3-dimensional tacto keyboard.

identification, even for 250-Hz stimuli, it is helpful to examine the amount of information transferred in each case. In fact, analyses of the data represented in Figure 7 indicate that for 250 Hz stimuli, overall correct identification was only at the 56% level, with only 1.11 bits of information transmitted (representing 2.15 tokens) out of the 2.807 bits potentially available in the 7 stimulus tokens. Similarly, when the stimulus frequency was 100 Hz, overall percent correct was 54%, and only 1.01 bits of information were transmitted (representing 2.01 tokens). When 12 tactors were tested (Figure 10), overall percent correct was 75%, and 2.52 bits of information were transmitted out of a potential 3.58 available in the stimuli, encoding 5.74 of the 12 tokens.

Further studies are being conducted to better explore the stimulus parameters that might influence vibrotactile localization, including, in particular, a parametric examination of stimulus frequency and tacto separation. Our intention is to optimize vibrotactile localization at each site so as to determine the design parameters for arrays used in cutaneous communication systems.

patterns. York: Pergamon.


