Chapter 2 – ANATOMICAL, NEUROPHYSIOLOGICAL AND PERCEPTUAL ISSUES OF TACTILE PERCEPTION

by

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In this chapter, we are concerned with what our touch receptors and the associated central nervous structures do. Our description begins with the anatomical and physiological characteristics of the touch receptors followed by a comprehensive psychophysical overview of touch sensation and perception. The conditions under which touch sensations and perception arise and the rules that govern them will also be described.

2.1 ANATOMICAL AND MORPHOLOGICAL CHARACTERISTICS OF TACTILE RECEPTORS

The anatomical and morphological characteristics of the touch receptors are well documented in numerous reviews [1][2, 3]. Only a brief summary is provided in this chapter. With respect to the sensation of touch, the innervations of the skin from various regions of the body are different from each other. There are some relatively elaborate structures associated with some of the nerve endings that respond to touch. There are also undifferentiated nerve endings that are involved in tactual response. The rapidly adapting mechanoreceptors present in the glabrous skin include Meissner's and Pacinian corpuscles. They are velocity-sensitive, discharging an impulse only during movement in the indentation of the skin. Meissner's corpuscles are encapsulated nerve endings that are located in the grooved projections of the skin surface formed by epidermal ridges. They can be found in abundance in the hand, the foot, the nipple, the lips and the tip of the tongue. Meissner's corpuscles are approximately 80 µm long, situated perpendicular to the skin surface. The receptor is connected to the skin surface by collagen fibres that enable the transmission of skin movement to the nerve endings in the corpuscle. They are sensitive to vibrotactile stimuli in the range of 10 – 100 Hz. Pacinian corpuscles are elliptical encapsulated endings, located in the deeper skin layers of both glabrous and hairy skin, which respond to rapid mechanical displacement of the skin. The Pacinian corpuscle is a layered structure, the mechanical characteristics of which limit the stimulus energy transmitted to the nerve endings to relatively high frequencies over the range of 40 – 600 Hz with optimal sensitivity around 250 Hz. There is a transient response to sustained mechanical displacement. The response is limited to the axonal membrane of the first node of Ranvier. Only one or two action potentials are seen when the generator potential is maintained at a steady level. Therefore, repetitive discharge does not occur in response to any steady component of generator potential that may be produced by temporal summation in response to repetitive stimulation. The receptor therefore produces impulses that follow the driving stimulus in the range of effective frequencies.

The slowly adapting mechanoreceptors include Merkel's disks and Ruffini's endings. They also discharge impulses in response to displacement of the skin; however, they can maintain a discharge of impulses in response to sustained deformation of the skin. These slowly adapting mechanoreceptors are sensitive to vibrotactile stimulation in the range of 0.4 – 400 Hz with varying characteristics and points of maximal sensitivity. Merkel's disks are found in the fingertips, the lips and mouth, with basket like terminations that surround hair follicles. Structures that look like Merkel's disks have also been found in epidermal domes that appear to be specialised receptor regions in the skin. The receptors are believed to respond to pressure applied perpendicularly to the skin at frequencies below 5 Hz. Ruffini's endings are situated in the dermis of both glabrous and hairy skin, deeper than Meissner's endings. It is believed that these receptors can provide continuous indication of the intensity of steady pressure or tension within the skin (e.g., lateral stretching).

Somatosensory information from mechanoreceptors ascends the central nervous system (CNS) by two main pathways: the dorsal-column medial-lemniscus pathway, and the anterolateral pathway. The dorsal column is made up of larger diameter axons from the dorsal root ganglion cells. It ascends ipsilaterally to the medulla and carries discriminative touch sensation, vibration sense, and information about joint and limb position. The anterolateral pathways originate from cells of the dorsal horn, cross at the spinal level, and ascend in the lateral columns, and carry information about pain, temperature sense, and crude touch. Also located in the lateral columns are the spinocerebellar tracts that are of importance in the cerebella control of movement. However, they do not contribute to the perception of somatic stimuli.

The lemniscal pathway consists of large myelinated axons, arising from A-beta sensory end organs (cutaneous mechanoreceptors that respond to pressure and vibration) located in the dermis of the skin. These axons course to the dorsal horn of the spinal cord, then branch into collaterals, which ascend in the posterior columns and terminate as climbing fibers on the dendrites of cells in layers III and V of the dorsal horn. Two ipsilateral tracts – the dorsal columns – form in the dorsal white matter of the spinal cord and ascend toward the cortex. Fibres from the lower extremities ascend in the gracile fasiculus, and fibres from the upper extremities ascend in the cuneate fasiculus. The dorsal columns terminate in the cuneate and gracile nuclei in the medulla. The axons synapse with neurons, decussate, and ascend in the medial lemniscus to the contralateral ventral posterior lateral nucleus (VPLN) of the thalamus. The VPLN also receive input from branches of the 5th cranial nerve, the trigeminal nerve, which transmits somatosensory information from the contralateral areas of the face. Neurons from the VPLN project to the primary and secondary somatosensory cortex, and to the parietal cortex, as well as sending collaterals to the reticular formation.

Phylogenetically, the anterolateral pathway is older; it conveys primarily pain and temperature signals from A-delta and unmyelinated Type-C end organs. The anterolateral pathway also conveys some tactile and joint information from A-beta fibres. Neurons that form the anterolateral pathway arise in layers I and II of the dorsal horn, decussate, and form three tracts on the anterolateral part of the white dorsal horn: the spinothalamic tract, the spinoreticular tract, and the spinotectal tract. The spinothalmic tract contains other A-delta fibers, similar to the dorsal-column of the dorsal-column medial-lemniscus pathway, and also projects to the VPLN of the thalamus. Both the anterolateral system and the dorsal column-medial lemniscal systems project to the posterior nuclear group of the thalamus. Many neurons in the posterior nuclear group receive converging projections from somesthetic, visual and auditory inputs and projects not to a specific cortical sensory area but widely, to many different regions of the cortex. As a result, the posterior nuclear group is thought to play a role in arousal. The somatosensory projection on the post central gyrus of the cortex is a horizontally distributed somatotopic representation of body geometry. In addition, there is a columnar organization of this region [4]. Neurons encountered in a microelectrode penetration perpendicular to the cortical surface are all of the same submodality and all have nearly identical peripheral receptive field locations.

2.2 PSYCHOPHYSICAL OVERVIEW OF TOUCH SENSATION

This report argues that there is a need for tactile displays, as well as demonstrates advantages when prototype display systems have been tested in the laboratory and field. But, to a large degree, there has not been a clear analysis of how to optimize the displays in any particular setting, nor for a particular body site (cref. Chapter 3). Before we discuss the possible ways to do this, a review of the manners in which the skin encodes information would be helpful. Furthermore, in these pages we hope to indicate the characteristics of the stimuli that should be attended to by applied researchers as they continue to develop and apply tactile displays.

The skin is a complex receptive organ, made more difficult to analyze because the receptor structures are buried deep in a multi-layered tissue matrix. The anatomical and physiological characteristics of skin have

been presented in the previous section. Suffice it to say that the structures that have been related to various types of tactile sensation (touch, vibration, temperature, pain) vary in their morphology, density, depth, and type as one moves from one point on the skin to another, and they are intermixed at any site. This kind of heterogeneous distribution leads to a number of implications for the development and application of tactile displays. Most importantly, one cannot depend on creating any particular unique sensation in a reproducible manner as one moves from body site to body site, or even from point to point, on the skin. A common demonstration of this "punctate" sensitivity is to lightly touch the point of a common pencil to various points on the back of the hand. The careful observer will notice that certain touches will feel "bright" or "cold." In fact, the "experimenter/observer" has just activated his/her tactile cold receptors. In the same way that these are sparsely distributed over the hand, so are the structures apparently responsible for vibratory perception as one moves from region to region over the body's surface. Weinstein [5] and Wilska [6] have demonstrated how several aspects of tactile sensitivity vary over the body's surface. Although there are methodological complications with some of these data [7], there is little question that the variation in receptor density apparent over a region as compact as an individual finger [8] is a microcosmic representation of what exists over the surface of the whole body. Sensitivity is a function of receptor density, with the fingers, lips, and genitals having the greatest thermal and spatial acuity. Furthermore, the areas of cortex devoted to their representation are proportional to innervation density [9]. These facts lead us to several design principles that will be relevant to any real-world cutaneous display technology. First, stimulation at a site will activate, to one degree or another, all tactile receptors – not just one specific type. Second, the active driving element (the "contactor") has to be of sufficient size to ensure activating at least some of these receptors, particularly on somewhat insensitive body sites like the abdomen or back. The following discussions of other characteristics of the physiological and perceptual characteristics of the skin will expand on these points and add additional principles to this list.

Verrillo and others have shown that the superior sensitivity of the skin to 250 Hz vibration only occurs for relatively large sizes of driver. Nevertheless, the Optacon, a 144-pin optical-to-tactile text converter used by the blind, was designed to vibrate at a high frequency with 0.25 mm pins [10], far below the minimum diameter to demonstrate the frequency sensitivity of the skin. In the years following, other tactors were designed (such as the Acoustical Engineering, Corp. Tactaid vibrators, or the Engineering Acoustics, Inc. C-2 drivers) to vibrate at these high frequencies. More and more data are accumulating to suggest that stimulus frequency might be irrelevant to the task at hand – some types of tactile pattern perception may not depend on this parameter. One example is the 25-year success of the Optacon. Given the poor spatial acuity of the Pacinian Corpuscles, the receptors intended to be driven by the stimulus frequency of the device [11], persons could, in practice, read vibrotactile text at over 100 words per minute (e.g., [12]). More recent data have shown that stimulus frequency may in fact not play a role in vibrotactile localization. Studies specifically comparing different tactor types have shown similar results (e.g., [13]) in which localization was not only independent of stimulus frequency over the range of 40 – 250 Hz, but over modes of stimulation (perpendicular indentation of the skin versus rotatory shear from pager motors). A reasonable question that can, therefore, be raised, is whether the findings of basic research have much to do with applied issues. Theory, based on carefully-controlled laboratory studies, argue one way, but when reality rears its ugly head, we find that, like vision and audition, touch seems to do better with the stimuli presented to the skin than one might expect knowing the physical parameters of the signal. Regardless of whether it is a pager motor, pneumatic tactor, high-frequency vibrator, or a mosquito, our ability to localize stimuli on the body seems to be better than we might expect. As in much of perception, the organism tries to extract the relevant parameters from the stimulus for the task.

If stimulus frequency (and the underlying primary receptor population) does not play a role, what factors can be assumed to affect the operation of a tactile display? There are several that should be taken into account. Of these, we will briefly discuss spatial resolution, adaptation and habituation, and age.

There is a considerable interest in creating high-density arrays of tactile stimulators. It is clear, however, from the data on the spatial resolution for touch, that the skin is not uniformly acute over its surface [14]

[5]. These data, however, have been collected only for durative pressure stimuli, not vibration, the dominant mode of tactile stimulation in display devices. In analyses of tactile resolution for vibratory stimulation, the required separation for accurate identification of individual sites (as might be required for targeting) is somewhat greater than one might expect. This is the case because vibration travels both over the surface and deep in the tissues that make up the skin (e.g., [15]). About three vibrating sites can be accurately localized (without error) on the forearm [16] while that number increases to seven evenly distributed loci on a belt around the abdomen [13]. These numbers were independent of stimulus frequency over the range of 40 to 250 Hz, as well as mode of stimulation. Even height around the waist did not affect this resolution: localization tactors around the waist 25 mm above the navel was identical to 100 mm above the navel. This was somewhat remarkable because of the extreme differences at the two levels in the underlying tissue – including ribs, muscle, and gut. Although we are unaware of comparable data in the literature regarding localization as a function of height on the trunk, successful displays involving 3 to 5 vertical rows of vibrators have been tested successfully to provide directional cues to operators [17][18][19][20], supporting the estimate from the information calculations. However, this limitation is only valid for identification tasks, which are fundamentally different from discrimination tasks. Work from TNO in the Netherlands suggests that the number of tactors around the waist for discrimination tasks can be much larger. Based on experiments measuring the spatial resolution on the torso, it was estimated that the number of stimulus sites that can be discriminated around the torso is on the order of 24 [21]. In direction discrimination experiments, the standard deviations found for sites around the torso are typically on the order of 10° [22], indicating that up to 36 tactors around the waist may be discriminable. Also, displays using much more than 3 – 8 tactors around the waist have been successfully tested (e.g., Van Erp et al. [23] used 24 columns around the torso).

The psychophysical studies discussed so far did not employ a very powerful tactile cue that has not yet been discussed: movement (the applied studies did, however). Extensive studies, particularly by Essick, have shown that even with very dense arrays, including far more loci than could be uniquely identified, judgments of the direction of apparent movement produced by sequential activation of tactors can be virtually perfect in many conditions. He studied a number of body sites with several types of stimuli, including moving brushes or probes as well as virtual motion on dense arrays of tactors, on the fingers, face, arm, and other loci, with similar results [24][25]. Testing seven sequentially activated sites on the forearm, subjects were essentially perfect in identifying the direction of apparent movement, regardless of spatial velocity [26]. These were the same sites and tactors which were used to test absolute localization, as described earlier. It was found that information about the loci of only 3 of the 7 was transmitted. When similar "moving" stimuli were generated over 12 sites surrounding the waist, the same sites described earlier in which only information about 6 were transmitted, direction of apparent movement was again perfectly identified [13, 16]. The principle to emerge from these results is that if possible, one should employ changes in the location of active tactors to encode the information to be transmitted.

Another less obvious advantage of moving stimuli is that they will reduce the possibility of another complication in tactile pattern generation: adaptation. Later in this section we will distinguish adaptation from the similar perceptual phenomenon, habituation. Adaptation may be generally defined as a reduction in sensitivity resulting from a continuous unchanging stimulus. Examples in vision, taste, and olfaction abound in everyday life. For example, our awareness of a smell in a room, whether pleasant or not, will often reduce or even disappear, only to return if we leave then return, confirming that it is not the stimulus but rather our response to it that has changed. With regard to touch, one of the reasons that we become unaware of the pressure of our clothes on our bodies is because of the mechanism of adaptation. But move an arm, and the changes at the edges of a sleeve or shoulder are immediately perceived. Adaptation occurs to durative suprathreshold stimuli and can disable or desensitize a given tactile channel [27], [28]). Typically, this occurs if vibratory stimuli last more than about 200 ms. If adaptation occurs, it is possible to still stimulate the skin by appealing to other channels by appropriate selection of stimulus frequency and amplitude. This is possible because adaptation to a frequency appealing to one channel (e.g., 250 Hz) has no effect on threshold at a frequency that appeals to another channel (e.g., 20 Hz).

In fact, adaptation with single contactors has been used to separate out the physiological channels described in the Bolanowski model (e.g., [29]) because of the absence of cross-adaptation. By these and other methods, the channels have been shown to be independent ([30][1]).

Habituation, on the other hand, occurs with repetitive stimuli but does not result in a change in the sensitivity of the sensory system. Rather, this appears to be an effect of attention. The everyday example of habituation occurs when we lose awareness of a ticking clock. If attention is drawn to the clock, we immediately become aware of the sound, so this indicates neither stimulus failure nor receptor desensitization. Should the clock skip a tick or change beats slightly, "dishabituation" occurs, and awareness returns. One way to address habituation and adaptation in an applied situation is to avoid long periods of stimulation. In flight, for example, this can be achieved by establishing null zone conditions in which tactor activation does not occur in stable situations such as straight and level flight or stationary hover. This prevents the operator from desensitizing to a continuous stimulus (adaptation) or to one that is constantly repeating (habituation). A pattern having a well-chosen stimulation duty cycle (e.g., off cycle is three times as long as on cycle) may prevent adaptation altogether [31, 32], although habituation may still be an issue.

Finally, if a tactile display is to be used by young and older persons, one might have to consider the changes in tactile sensitivity and acuity that occur with aging. A number of survey articles have discussed these changes in detail (e.g., [14][33][34]). Even if the intended population is only older, it is likely that the data that contributed to the development of the tactile display were collected on a younger population – usually college-age students. This has been a particular problem with devices intended to help in cases of sensory handicap. The population that is most commonly afflicted with these is older than 60 years – the population showing deficits in spatial acuity, vibrotactile sensitivity, and temporal resolution (e.g. [16] [35][33][14][34]). However, it has also been reported that in an operational setting, older observers (60 to 70 years) performed as well as the ones between 40 – 50 years old in detection threshold and spatial and temporal resolution [36][37].

2.3 AVAILABLE PSYCHOPHYSICAL DATA RELATED SPECIFICALLY TO THE CONDITIONS UNDER WHICH TOUCH SENSATION AND PERCEPTION ARISE

2.3.1 Difference Threshold

The difference threshold is the amount of indentation that is related to the minimal required change in amplitude to be detected. Craig [38] reported that the Weber fraction ($\Delta I/I = K$, where I is the stimulus intensity and K is the constant) for tapping depends on the stimulus intensity. Higher Weber fractions result from low intensities (0.35 at 15 dB) and lower Weber fraction for higher intensities (0.25 for 25 dB and higher). For bursts, the Weber fractions were 0.20 and constant over the range of stimulus intensities (15 – 35 dB). In addition, background vibration [38], and adaptation [39] also have an effect on the difference threshold.

2.3.1.1 Absolute Detection Threshold

Sherrick and Cholewiak [40] indicated that the absolute threshold for vibrotactile stimuli for the trunk is 4 microns at 200 Hz. A more extensive study by Wilska [6], who measured thresholds for 200 Hz vibration over the body, suggested a threshold of 4 microns in the lower part, 2 microns in the upper part, and 4 microns in the dorsal side of the torso. Verrillo [41, 42] measured thresholds for vibrotactile stimuli on the glabrous skin as a function of frequency, location and several contactor properties. The threshold as a function of frequency was U-shaped with a maximum sensitivity in the region of 250 Hz. However, this value is only valid for relatively large contactor areas. Verrillo [43] also determined absolute

thresholds as a function of frequency on the hairy skin of the volar forearm. There were two marked differences with the results found with glabrous skin. First, thresholds on hairy skin were higher than those on glabrous skin. Second, the maximum sensitivity shifted from 250 Hz for glabrous skin to 220 Hz for hairy skin. The thresholds for force as measured by Weinstein [5] are in the order of 60 – 80 milligrams for the torso. Other factors that have an effect on the absolute threshold are the contactor lay-out [35], the presence of a rigid surround, how deep the contactor is pressed into the skin [41, 42], waveform, and temperature [44].

2.3.1.2 Subjective Magnitude

The intensity of a stimulus is often indicated with reference to the absolute threshold of the stimulus (dB SL). However, stimuli with the same objective intensity level are not necessarily perceived to be equal in subjective intensity, and doubling the objective intensity or amount or energy does not necessarily result in a doubled subjective intensity. Verrillo, Fraioli and Smith [45] found that the subjective magnitude as a function of objective magnitude is a power function with an exponent around 1 (i.e., close to linear). Other factors that have an effect are the stimulus duration [46], the number of successive bursts [47], the presence of static surround [48], the frequency and intensity of a preceding stimulus [47], and the number of simultaneous vibrators [49]. As a coding parameter, (subjective) intensity seems less appropriate, and not more than four different levels should be used between the detection threshold and the comfort/pain threshold [38].

2.3.1.3 Spatial Summation

Sherrick and Cholewiak [40] concluded that the sense of touch exhibits spatial summation (change in threshold as a function of the area of stimulation), but that it is small and probably a central and not a peripheral process. Makoes et al. [50] investigated spatial summation under different conditions. Their results suggested that spatial summation exists for all types of skin under high frequencies. However, for low frequencies, spatial summation was present on the hairy skin of the forearm but not on the glabrous skin of the hand. Other factors that have an effect are skin indentation, pressure and force [51], intensity level [52], and the number of loci [53].

2.3.1.4 Psychophysics of Localization

Issues relevant to the perception of stimulus location are: how well one can determine the location of a stimulus (absolute localisation), how well can one distinguish different locations from each other (relative localisation or the spatial resolution of the skin), and how can spatially separated stimuli influence each other (spatial masking).

2.3.1.5 Spatial Acuity of the Skin

Spatial acuity has been investigated by several methods, including two-point discrimination, gap detection, grating resolution, and letter recognition [54]. It should be noted that most studies used pressure and not vibrotactile stimuli to measure spatial acuity [16] and that most studies investigated the fingertips only. Because vibratory stimuli act upon different sensory receptors and result in both longitudinal and shear waves that may degrade spatial resolution (see [55] for wave propagation models for the skin), results using pressure stimuli may not be generalised. A classic study by Weinstein [5], who measured thresholds of two-point discrimination and tactile point localization on several body loci using pressure stimuli, demonstrated that there is an enormous difference between different body loci (see also [14]). Lowest thresholds were found for the fingertips, about 2 mm. Thresholds for the trunk were much larger, up to 4 cm. The sensitivity decreased from distal to proximal regions (see also Vierodt's law of mobility; [56]), and acuity correlated with the relative size of cortical areas subserving a body part [9]. Other factors that have an effect on spatial resolution are temperature of the objects that are touched [57] and of the skin

itself [58]. The frequency range of the vibration appeared to have little effect on spatial localization, and the apparent points were more difficult to localize than physical points [59]. Regarding hyperacuity in tactile sensation, it has been shown that the thresholds for frictionless shifts in the position of a point stimulus on the torso [60] were 10 – 30 times smaller than the resolution reported by Weinstein [5]. In addition, judgments of the direction of apparent motion induced by dense arrays of tactors are much better than predicted on the basis of local spatial resolution [24, 25]. Recently, important work on stimulus identification and discrimination was published. Cholewiak, Brill and Schwab [13] concluded that the number of unique stimulus sites that can be identified around the torso is about seven. Van Erp [21] found that the spatial resolution around the torso for vibrotactile stimuli is relatively uniform over the torso and in the order of 3 cm.

2.3.1.6 Psychophysics of Temporal Events

The role of time in cutaneous perception includes temporal resolution (acuity) of the skin, temporal masking, summation effects and also adaptation. Temporal acuity is the minimal difference in the time domain required to distinguish two stimuli including temporal order (which came first), duration, and gap detection. Several methods have been used to measure temporal acuity, such as temporal numerosity [61]. Unimodal threshold studies have shown that the temporal resolution of the skin lies between those of hearing and vision [62]. This relationship extends to discrimination of duration [63], synchronization of finger taps [64], and adjusting empty intervals to equal pulse duration. Hirsh and Sherrick [65] investigated the perception of temporal order (i.e., the ability to judge which of two successive tactile events came first), where the observers had to judge the temporal order as well as which pattern was presented first. The results demonstrated that an increase in temporal separation also increased the percentage of correct distinctions between the stimuli. With a 20 ms separation, this percentage was 75%. This 20 ms threshold is larger than that obtained for successiveness measurement only. Gescheider [66] measured the perception of successiveness as the ability of observers to distinguish between successive and simultaneous events. He showed that two stimuli of 1 ms must be separated by 5.5 ms to be perceived as two stimuli at a single locus on the fingertip. Petrosino and Fucci [67] measured thresholds of successiveness as the ability to accurately count a series of events presented within a temporal epoch and found that thresholds increased with age and locus that ranged from 13 to 30 ms. Craig and Baihua [68] measured temporal order judgements for stimuli presented to a single fingerpad (same site), to two fingers on the same hand (ipsilateral), or to two fingers on opposite hands (bilateral). Thresholds were 12 ms for the same-site condition, 65 ms for the bilateral condition and 125 ms for the ipsilateral condition. In a controlled experiment, subjects judged which of two locations received a pattern first when the same pattern was delivered to both locations. Thresholds for the bilateral and ipsilateral condition were similar to those obtained by Hirsh and Sherrick [65], although they used a 1 ms-pulse instead of a vibration stimulus of 26 ms.

2.3.1.7 Short Burst Duration

In general, stimuli with short burst durations (BDs smaller than 30 ms) are hypothesised to be processed differently by the nervous system [69 – 71], although direct psychophysical data are not available. For example, Hill and Bliss [72] suggest that for small BDs, the sequence of the presentation but not the content is lost when 24 inter-joined regions of the fingers were stimulated. Kirman [71] suggested that a larger stimulus onset asynchrony (SOA) is required for stimuli with smaller BD to be felt as successive instead of simultaneous stimulation. In order to perceive smooth apparent motion, a steeply rising SOA is required for BD values below 30 ms.

2.3.1.8 Temporal Difference Thresholds

Very few studies have investigated the difference thresholds in the Weber fractions for temporal intervals. The Weber fractions ranged from 0.10 [73][74][63] to 0.25 [75] for stimulus durations shorter than 1 s.

Van Erp and Werkhoven [76] found that the Weber law holds over the range of empty intervals between 100 – 800 ms, with a Weber fraction of 0.20.

2.3.1.9 Temporal Summation

The relationship that exists between the duration of a stimulus and the threshold required for detection is known as temporal summation. Verrillo [77] found effects of summation to require a minimal area of stimulation. Summation effects were found up to durations of 1000 ms. For taps, temporal summation is exponential for the range 1 – 10 ms and constant for 10 – 100 ms.

2.3.1.10 Adaptation

Adaptation corresponds to a change in the percept of a stimulus after prolonged stimulation. The absolute threshold increases and the magnitude of sensation decreases with increasing adaptation. The time constant of the adaptation process is approximately 2 min [78]. The effects can be found up to 25 min, after which the change in threshold is about 17 dB and the change in sensation about 6.5 dB. Recovery time is approximately half the duration of the adaptation time [31, 32]. Adaptation does not occur across frequency bands [47, 78, 79]. O'Mara et al. [80] reported that extended exposure to a vibratory stimulus produced substantial changes in the responsiveness of subcortical cells but not in the peripheral afferents, suggesting that vibrotactile adaptation is largely a central process.

2.3.1.11 Frequency of Stimuli

As with the other parameters, one can also manipulate the frequency of stimulation. However, when the frequency varies, care must be taken to maintain constant subjective intensity since subjective magnitude of vibrotactile stimuli is frequency dependent. Goff [81] found that the Weber fraction of frequency increased with increasing frequency and for stimuli with a lower intensity, and ranged between 0.18 and 0.55. Cohen and Kirman [82] demonstrated that thresholds increased for stimuli with a duration of 30 ms. The Weber fractions were reported to be on the order of 0.20 – 0.25 for frequencies between 20 and 300 Hz [83]. Goff recommends that frequency should not be used as an information parameter in tactile communication systems at high frequencies.

2.3.1.12 Spatiotemporal Perception

The perceptions of apparent motion, apparent position, and relative location of two or more consecutively presented stimuli (point localisation) when using vibrotactile stimuli are based on the processing mechanisms of spatiotemporal patterns. This implies that there is a potentially powerful mechanism that is able to integrate place and time. For example, judgments of the direction of apparent motion can be more accurate than spatial resolution performance [24, 25], but may also result in masking effects. Spatiotemporal processing in the primate and human brain is presumably based primarily on location, lateral inhibition and facilitation. Through these processes, neurons sensitive to specific spatiotemporal patterns were developed. This assumption is logical because representations in the somatosensory cortex and other areas involved in the processing of somatosensory stimuli are location based (also called somatotopic). Spatial relations are carefully preserved in the neuronal pathways and in the representations in the cortex.

2.3.1.13 Sensory Saltation

Saltation [84 – 86] refers to the area where mislocalisation occurs for two successive and spatially separated stimuli. They can be found over the whole body, but never cross the body midline. Their size and form are related to those of the cortical receptive field (RF). The process exists for strict timing parameters, of which the inter-stimulus interval (ISI) has a major influence. BD must be in the order of

5 ms. The vividness and strength of the saltatory effect is supported by psychophysical data from a study done by Cholewiak and Collins [26]. They investigated the perception of different line qualities (e.g., length, smoothness) under veridical and saltatory presentation modes as functions of the timing parameters. They concluded that there were no differences between the two modes.

2.3.1.14 The Cutaneous Rabbit

The cutaneous rabbit is the name given to a spatiotemporal perceptual illusion that made the researchers conjure up a vision of a tiny rabbit hopping over their body [87]. The rabbit illusion also occurs under strict temporal parameters. Again the BD must be very short (i.e., a tap in the order of 2 ms). This illusion is based on a series of these taps, delivered to two separate locations, with multiple taps at the first location. When the timing between the taps is correct, the observer perceives numerous individual taps spaced between these two locations. This sensation resembles both saltation and apparent motion, except for the fact that individual taps are perceived instead of continuous motion. For ISIs larger than 200 ms, the effect is absent. For ISIs between 200 and 100 ms, the displacement starts, with the taps more or less evenly spaced at 100 ms ISI. The illusion is optimal for ISIs between 40 and 60 ms for a five-tap rabbit. The number of taps becomes illusory for ISIs below 40 ms. The importance of the timing parameter is confirmed by the fact that gaps in the stream seriously degrade the illusion. Besides the ISI, the number of taps is also important but not the distance: 2 taps are sufficient, 4 – 6 is optimal, 18 taps are too much. The “rabbit” sensation can cross the body midline only if one of the locations is on the body midline. The illusion is very strong when both locations are within the same dermatome, but very weak or absent between dermatomes [87].

2.3.1.15 Apparent Motion

Apparent motion is a perceptual illusion in which two or more non-moving stimuli activated in a specific spatiotemporal pattern evoke a percept of continuous motion. The percept is not always stable. Although mentioned in the early psychophysical literature (e.g., [88]), it was not until the 1960s that researchers were able to evoke a reproducible effect [69, 70, 89]. Sherrick reported that apparent movement could be induced by successive bursts of vibration but not by pressure stimuli, which yield unreliable judgements of movement. It has been shown that the significant variable for the appearance of ‘good’ movement is the interval between onsets of stimuli, or the stimulus onset asynchrony (SOA). Sherrick investigated which variables determined the optimal SOA for good movement. The following variables had no effect on the quality of movement or the optimal SOA: vibration frequency (60 – 250 Hz), body locus (forearm, back, stomach, hand), subjective magnitude (6 – 30 dB SL, see also [90]), direction of motion (proximal-distal or vice versa) and magnitude imbalance (when one stimulus had twice the intensity of the other). Burst Duration (BD) was crucial for good apparent movement: the optimal SOA varied linearly with BD in the range between 25 and 400 ms (with SOA about 0.70 of the BD, and an offset of 60 msec). Kirman [71] used a subjective rating method to measure the quality of apparent movement. The degree of apparent movement varied as a function of SOA: the function first increased and then decreased. Both the optimal SOA and the impressiveness of apparent movement increased with a BD above 20 ms. Apparent motion is thus an illusion that is mainly related to timing parameters (and the number of stimulus sites, [91]).

When the required SOA for apparent motion is plotted as function of BD, the typical pattern shows a decreasing SOA for BD values until a bottom value around 30 ms (which is equivalent to a decreasing ISI for larger BDs as found in [92]) is reached. For BDs above 30 ms, the required SOA increases again [71, 92]. This typical pattern is absent in studies that did not use BDs near or below 30 ms. What is remarkable about the dip is that it is located near the threshold for temporal order and the critical BD value below which stimuli are hypothesised to be processed differently.

2.3.1.16 Pattern Recognition

Pattern recognition (i.e., the identification and discrimination of patterns, see also [93]) as a function of timing parameters has not extensively been studied. Cholewiak and Craig [94] report that their data is more accurately described by SOA than ISI.

2.3.1.17 Masking

Masking is a change in the percept of a stimulus (target) when a second stimulus (masker) is close in time and/or space. The masker may (negatively) affect several aspects of the target, including the absolute threshold, the difference threshold (e.g., [95]), and the perceived location. Furthermore, observers may respond to the masking stimulus as though it was the target (also called response competition, which assumes that both target and non-target interfere at a later state of processing [96, 97]). Temporal masking occurs when two patterns occupy the same location at different times. In general, the interference between the patterns decreases when the temporal separation between the onsets of the two patterns increases. The masking pattern can be presented prior to the pattern to be identified (forward masking) or subsequently to the target pattern (backward masking). Both types do not always result in the same amount of masking [98]. At brief SOAs (< 100 ms) they found more backward than forward masking. However, when the SOA was relatively long (> 200 ms) backward masking became negligible whereas forward masking remained visible for SOAs up to 1200 ms. This is consistent with the results reported by Bliss et al. (1966). However, Gescheider, Bolanowski and Verrillo [99] did not find any differences and Weisenberger [100] reported more forward masking than backward masking for relatively short ISIs. The difference between the above mentioned studies might be due to the difference between signal detection [99, 100] and pattern recognition [98, 101]. It is possible that different processes are involved in detecting simple vibrotactile signals and in recognising complex patterns of stimulation. Other factors that may affect the amount of temporal masking are the type of masking stimuli [102] and the frequency of the stimuli (no cross-channel masking [103]). Spatial masking occurs when two stimuli occupy two locations but at different (possibly overlapping) times. Sherrick [104] measured the detection threshold of a pulse masked by a second pulse as a function of the ISI and the spatial distance. He demonstrated that the amount of masking decreased when the spatial separation between the two stimuli increased. He also found that contralaterally placed maskers showed masking effects, which indicates that the interaction between the pulses is not solely a peripheral process but also requires some degree of central involvement. Verrillo and Gescheider [103] found masking (increased detection thresholds) predominantly for high frequency stimuli. A very specific situation occurs when a target is masked by another stimulus that is presented at the same location and at the same time. Gescheider, et al. [105] measured this by presenting a specific target (an amplitude change) in a continuous white noise vibration. The thresholds increased with increasing masking intensity. Finally, masking can occur when target and masker overlap neither in time nor in space (although they are in close proximity both spatially and temporally). Weisenberger and Craig [106] instructed subjects to identify vibrotactile patterns presented to their left index fingertip in the presence of spatially adjacent masking stimuli. Forward and backward masking decreased with increasing SOA (although actually ISI is a better term to indicate the amount of overlap). Maximum interference in pattern recognition was found to occur at an SOA of about 50 ms.

2.3.1.18 Models for Spatiotemporal Processing

In general, the psychophysical theories do not agree on the specific mechanisms underlying spatiotemporal integration or masking phenomena. Some theories on masking are discussed briefly. Bliss et al. [101] described masking with a model consisting of three intervals:

1) A read-in interval of 50 to 100 ms in which stimuli occurring in the interval are superimposed;
2) A period of 75 to 200 ms in which a second stimulus may cancel or replace the first stimulus because both stimuli occur in the same temporal epoch; and
3) An interval in which the mutual interference between the two stimuli is reduced.

Craig [102] and Craig and Evans [98] suggested that temporal masking obtained with vibrotactile patterns occurs because of two processes: interruption and integration. Interruption arises when the features of a target are distorted or confused with features of a masker. It is responsible for producing greater amounts of backward masking than forward masking. Temporal integration operates in both backward and forward masking paradigms. Two patterns that are presented in close temporal and spatial proximity are integrated into a composite form in which the target pattern is obscured.

Craig and Evans [98] argued that the presentation of a vibrotactile pattern yields an internal representation that persists following the cessation of a stimulus for a certain amount of time. They demonstrated that forward masking occurred for SOAs up to 1200 ms. The information contained within the tactile sensory store decays rapidly at first (until SOA = 100 ms) and decays at a slower rate (until SOA = 1200 ms). Backward masking is strong at SOAs < 100 ms since information presented to the same place of the skin is integrated over a temporal window of approximately 100 ms. The reason that at relatively long SOAs there is more forward masking than backward masking is that the representation of a pattern persists for about 1200 ms.

Gescheider, Bolanowski and Verrillo [99] mentioned that according to Kirman [107], forward masking may be primarily a peripheral interaction maximally evident when peripheral interaction between target and masker occurs, while backward masking has a strong central component. However, Craig and Evans [98] discussed that the persistence of features of vibrotactile patterns after stimulation, which explains forward masking at long SOAs, is probably not a peripheral process. Gescheider et al. [105], who found that the effect of a masking stimulus on the vibrotactile threshold was independent of frequency, concluded that either the neural processes responsible for vibrotactile masking must be the same for each vibrotactile channel or the process operates at a level in the central nervous system that integrates information across the psychophysical channels. However, the first conclusion seems to be more likely, since Verrillo and Gescheider [103] found that masking did not occur between these channels.

2.4 CONCLUDING REMARKS

This chapter describes the anatomical and psychophysical aspects of the sense of touch. It shows that the sense of touch is very complex, consisting of many specialized receptors and cortical projections. Although the body of psychophysical data is much smaller than for the visual and auditory senses, the information required to design vibrotactile displays is available. Basic information on factors such as the spatial and the temporal resolution is available and presented here. However, data on other stimuli than pressure or vibration (for instance electrocutaneous signals) are still sparse. With respect to vibration stimuli, it can be concluded that location and timing are the two most important stimulus parameters, also strongly interacting with each other. This can for example result in apparent motion and spatial masking. Psychophysical data are especially relevant to the human factors of tactile displays, which will be discussed in Chapter 3.

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