

**ACTIVE AND PASSIVE PROCESSING OF
SEQUENTIAL TACTILE INPUTS**

by

Ali Murat

B.S., E.E., Eastern Mediterranean University, 2002

Submitted to the Institute of Biomedical Engineering
in partial fulfillment of the requirements
for the degree of
Master of Science
in
Biomedical Engineering

Boğaziçi University

September 2006

**ACTIVE AND PASSIVE PROCESSING OF
SEQUENTIAL TACTILE INPUTS**

APPROVED BY:

Assistant Prof.Dr. Burak Güçlü
(Thesis Advisor)

Prof.Dr. Reşit Canbeyli

Assoc. Prof.Dr Hale Saybaşılı

DATE OF APPROVAL:

ACKNOWLEDGMENTS

I would like to express my sincere thanks to my thesis supervisor, Assistant Prof. Dr. Burak Güçlü. He provided me with necessary support, advice, facilities and enthusiasm required to successfully complete this thesis. His efforts in helping me in the experiments are much appreciated. I would like to thank to Dr. Zafer Tandođdu, who provided me with valuable support in the subject of somatosensory system. I also would like to thank Serkan Çelik and Buđra Bayraktar for his support and assistance throughout the progress of this thesis.

ABSTRACT

ACTIVE AND PASSIVE PROCESSING OF SEQUENTIAL TACTILE INPUTS

In this thesis, a psychophysics experiment, which is designed to test the effect of active and passive touch on tactile temporal processing, is presented. Active and passive touch are terms that were defined first by J.J. Gibson, and there have been many experiments done where these two were compared. Most of these studies made the comparison in the dimension of tactile spatial processing. In this study however, the subject is asked to detect the tactile stimuli applied at certain time intervals. Therefore, tactile temporal processing was tested here. The tactile stimuli were applied both actively and passively, and the correct judgments of the subjects were recorded at both conditions. Besides active/passive touch, the effects of visual attention and scan velocity on tactile temporal processing were tested in this study.

Keywords: Active touch, passive touch, temporal processing, cognitive processes.

ÖZET

ARDIL DOKUNSAL UYARILARIN AKTİF VE PASİF İŞLENMESİ

Bu tez çalışmasında, aktif ve pasif dokunmanın zamansal işlemlerdeki etkisini ölçmek için hazırlanan psikofiziksel bir deney çalışması sunulmaktadır. Aktif ve pasif dokunma tanımlamaları ilk olarak J.J. Gibson tarafından yapılmış, ondan sonra bu iki farklı dokunmanın kıyaslandığı birçok deney yapılmıştır. Bu deneylerin birçoğu kıyaslamayı uzaysal işleme boyutunda ele almıştır. Bu çalışmada ise tespit edilmesi istenilen şey, belli zaman aralıklarında eşit şekilde uygulanan dokunsal uyarılardır. Anlaşılacağı üzere burada söz konusu olan mekanizma dokunmadaki zamansal işlemlerdir. Bu dokunsal uyarılar aktif ve pasif olarak uygulanmış, deneklerin iki durumda da uyarıları ne kadar algıladıkları ölçülmüş ve kıyaslanmıştır. Aktif/pasif dokunma yanında, görmenin ve tarama hızının da birer faktör olarak dokunmadaki zamansal işlemler üzerindeki etkileri test edilmiş ve gösterilmiştir.

Anahtar Sözcükler: Aktif /pasif dokunma, zamansal işlemler, kognitif işlemler.

TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	iii
ABSTRACT.....	iv
ÖZET.....	v
TABLE OF CONTENTS.....	vi
LIST OF FIGURES.....	viii
LIST OF TABLES.....	ix
LIST OF SYMBOLS.....	x
LIST OF ABBREVIATIONS.....	xi
1. INTRODUCTON.....	1
2. TACTILE PERCEPTION.....	4
2.1 Cutaneous Sense	4
2.2 Kinesthetic Perception	4
2.3 Haptic Perception.....	5
2.4 Active and Passive Touch.....	5
2.5 Phenomenology of Touch.....	6
3. SOMATOSENSORY SYSTEM.....	8
3.1 Peripheral Mechanisms.....	8
3.1.1 Skin	8
3.1.1.1 Structure.....	9
3.1.1.2 Innervation and Receptor	10
3.1.2 Peripheral Coding.....	12
3.1.2.1 Cutaneous Mechanoreceptor Channels and Functional Specificity	13
3.1.2.2 Kinesthetic Mechanoreceptors.....	14
3.2 Central Somatosensory Pathways.....	15
3.2.1 Ascending Somatosensory Pathways.....	15
3.2.1.1 The Medial Lemniscus System.....	15
3.3 Cortical Processing	17
3.3.1 Cortical Organization.....	17
3.3.1.1 Cortical Areas	18
3.3.3 Functional Organization	20
3.3.3.1 Tactile Feature Perception	20

3.3.3.2 Haptic Processing	20
4. COGNITIVE TACTILE PROCESSES	22
4.1 Information Processing Model.....	22
4.2 Tactile Short-Term Memory	24
5. METHODS	25
5.1 Subjects	25
5.2 Materials	25
5.3 Procedure	27
6. ANALYSIS AND RESULTS.....	32
6.1 Analysis	32
6.2 Results.....	32
7. DISCUSSION	38
REFERENCES.....	41

LIST OF FIGURES

Figure 3.1	The skin.....	9
Figure 3.2	The Pacinian corpuscle.....	12
Figure 3.3	Medial lemniscus system.....	16
Figure 3.5	The Somatosensory Cortex.....	19
Figure 4.1	Schematic representation of human information processing system.....	23
Figure 5.1	One meter stick covered with small nails.....	25
Figure 5.2	Block diagram of the apparatus.....	26
Figure 5.3	Device designed to detect start/end of scan (enable circuit).....	26
Figure 5.4	Enable circuit, digital counter, and the function generator.....	27
Figure 5.5	Experimental setup for active touch.....	28
Figure 5.6	Active touch (eyes are open/eyes are closed).....	29
Figure 5.7	Apparatus designed for passive touch.....	30
Figure 5.8	Index finger fixed on the apparatus.....	31
Figure 5.9	Passive touch.....	31
Figure 6.1	Relative errors at each scanning speed in active and passive touch (a)eyes closed , (b) eyes open.....	33
Figure 6.2	Relative errors in eyes open and eyes closed condition. (a) active touch, (b) passive touch.....	33
Figure 6.3	Relative errors for pooled data: (a) active vs passive touch, (b) eyes open vs eyes closed,	34
Figure 6.4	Relative errors as a function of scanning speed.....	35
Figure 6.5	Relative errors for active and passive touch in (a) female subjects, (b) male subjects	36
Figure 6.6	Relative errors of male an female subjects in (a) active touch, (b) passive touch.....	36

LIST OF TABLES

Table 6.1	3-way ANOVA results.....	34
-----------	--------------------------	----

LIST OF SYMBOLS

f	frequency
v	average speed

LIST OF ABBREVIATIONS

PC	Pacinian Corpuscle
PNS	Peripheral Nervous System
CNS	Central Nervous System
SA	Slowly Adapting
RA	Rapidly Adapting
VPL	Ventroposterolateral
VPM	Ventroposteromedial
S	Slow
MS	Medium Slow
MF	Medium Fast
F	Fast
RT	Reaction Time

1. INTRODUCTON

In everyday life we attach great value to vision and hearing for the roles they play in making us aware of surroundings. These are sensory systems that provide us with information about our 'external environment'. For most of us, sight and sounds are our primary source of knowledge of the outside world; odor and taste are somewhat less useful. Information about things in our remote environment (clouds) can only be obtained through sight. Hearing can tell us about closer objects, but with less accuracy. Odor and taste are more restricted still. Smell, when available, can only be used over a circumscribed region while taste is primarily used to tell us about the chemistry of substances and requires intimate contact. Most of the time we tend to underestimate the role of touch in our perception of the world. In contrast to the modalities mentioned above, touch is primarily important because of what it tells us about ourselves. First, our contact with the outside world is mediated by sensory receptors in the skin. Second, knowledge of our movements and body position is obtained from sensory receptors in muscles and joints. Touch facilitates all motor activity, permits the perception of nearby objects and spatial layout when viewing is not feasible, and informs us of object properties (e.g. temperature) and events (e.g. vibrations) inaccessible to the other senses. The potential role of touch could furtherly be exemplified by the achievements of those who have lost one or both of the major senses. The blind rely mainly on the sense of touch in their activities.

The research literature acknowledges that the "sense of touch" in fact comprises two distinct senses—the cutaneous sense and kinesthesia [1]. Viewed functionally, the cutaneous sense provides awareness of stimulation of the outer surface of the body by means of receptors within the skin and the associated nervous system, whereas the kinesthetic sense provides the observer with an awareness of static and dynamic body posture (relative positioning of the head, torso, limbs, and end effectors) on the basis of (1) afferent information originating within the muscles, joints, and skin and (2) efference copy, which is the correlate of muscle efference available to the higher brain centers [2].

While J. J. Gibson acknowledged these two components of the sense of touch, he believed that analysis of the touching process must be done in other terms [1]. In most of his writing including the discussion of his frequently cited experiment comparing the two modes, Gibson equated **passive touch** with what is more frequently termed "tactile perception". This is perception based solely upon stimulation of the cutaneous sense of an immobile observer.

Active touch on the other hand meant purposive exploration of the stimulus field. Thus, in addition to the cutaneous information available to the passive observer, the active observer has the information provided by afferent and efferent kinesthesia as well as the ability to control the pickup of information. When permitted to examine an object actively, the observer does not attend to the particular momentary sensations but rather seeks over time and space the variances in the stimulation that characterize the object being explored. These are going to be discussed in detail in section III.

Interest in the use of tactile information displays has grown rapidly in recent years. Tactile information is encoded both spatially, by differential activation of adjacent receptors and temporally, by changes in receptor activation during movement. Active and passive touch has been compared several times where spatial processing of sensory inputs was involved. Lederman compared active and passive touch in detecting surface roughness [3]. Vega-Bermudez and Johnson [4] compared them in tactile feature extraction. However, relatively little research has been conducted to explore any cognitive and/or attentional mechanisms and limitations while the tactile information is encoded temporally as in our case. The comparison of active and passive touch by the method, which is going to be described in section V, was in part be an exercise in tactile temporal processing. In the experiment, the subjects were asked to detect tactile stimuli applied at certain time intervals. It is therefore appropriate to explore the processing of temporal and sequential stimuli by the tactile system.

Sequential processing of sensory inputs has been typically studied in relation with temporal order judgement. Two main theories have been proposed to explain the perception of temporal order of sensory events: the central-timing theory and the feature-

specific theory. Pöppel [5] argued that the functional states of temporal perception are implemented by neuronal oscillations and they have approximately 30-ms durations. Many human studies support this hypothesis which implies a central-timing mechanism independent of the sensory modality. Temporal-order thresholds are approximately the same for auditory, visual, and tactile stimuli[6]. For example, at about 40-ms inter-stimulus interval, the temporal order of auditory and visual stimuli can be judged with high (i.e. 75%) correctness [7]. On the other hand, if stimulus properties are varied substantially, e.g. auditory versus clicks, feature-specific mechanisms may also arise. Fink [8] found very different threshold distributions when two auditory clicks were tested against two tones, and when two visual positions were tested against two colors. The thresholds for two-click and two-position stimuli were distributed more or less evenly about the mean 40-60 ms. However, the threshold distribution for two-tone stimulus mimicked an exponential distribution with mean 31 ms. The two-color stimulus produced an approximately symmetric threshold distribution with mean 107 ms. These results show that the two theories of temporal perception mentioned above are probably not mutually exclusive. It may be hypothesized that if a central-timing mechanism dominates sequential processing, additional sensory cues contributed by active touch should not improve the performance. However, a feature-specific process is expected to be greatly affected by active touch.

In the thesis three hypotheses were tested:

1. Accuracy of detecting sequential tactile signals is higher in active touch compared to passive touch.
2. Visual attention would increase the accuracy of detection.
3. Increase in the scan velocity would decrease the accuracy of the detection.

Quantitative results for theoretically projected cases mentioned above were acquired so that there would be the chance to understand some of these cognitive mechanisms and limitations. This information may be applied 'machine haptics'. Training of medical skills, procedures and devices is an application in medicine. Combat simulation is another application in the military. There are also various applications in design and engineering, in education, and in entertainment, where tactile information in time and space is important.

2. TACTILE PERCEPTION

The fact that the cutaneous sense contributes to kinesthesia prohibits a sharp division between the two in terms of mechanism but not in terms of function. Accordingly, this section is organized in terms of the contributions of these two senses to the “sense of touch”; what follows is a representation of the three resulting categories of tactile perception. The term *tactile perception* is employed in the section to refer inclusively to all perception mediated by cutaneous sensibility and/or kinesthesia [1].

2.1 Cutaneous Sense

Cutaneous sense refers to perception mediated solely by variations in cutaneous stimulation. It is recognized that the perception always occurs within the context of a particular static posture, and that the perception sometimes depends upon what that posture is. However, provided that the posture remains constant, the variations in stimulation that control tactile perception are solely cutaneous.

2.2 Kinesthetic Perception

Kinesthesia comes from *'kine'*, the Greek word for movement, and literally refers to our sense of movement. Our kinesthetic sense encompasses sensations associated with position and movements of joints, which originate from specialized joint receptors. In addition, it is customary to include signals received from muscle receptors, which provide information about force and effort associated with muscular contractions, and about timing of muscle contractions [9].

The focus here is on perception mediated exclusively or nearly so by variations in kinesthetic stimulation. There is no cutaneous contribution, such as in experiments where cutaneous sensibility has been completely eliminated by anesthesia or circulatory occlusion. Under some circumstances like these, one would expect observers, on the basis of resistance to limb movement alone, to be able to perform a variety of perceptual tasks,

such as judging the hardness of materials or the viscosity of liquids and perceiving the shape of large three-dimensional objects. Included in the category of kinesthetic perception are those cases of tactual perception where variations in cutaneous stimulation do not inform the observer of their spatial or textural properties. One example would be the identification of a raised pattern traced by a finger that is covered by a thimble. Another would be discriminating between lengths of rods, the ends of which are held between the finger and thumb. In both examples, the cutaneous stimulation serves only to indicate contact with the stimulus, while variations in kinesthetic stimulation convey all of the spatial information essential to performance of the task.

2.3 Haptic Perception

The term haptic perception refers to tactile perception in which both the cutaneous sense and kinesthesia convey significant information about distal objects and events. Most of our everyday tactile perception falls into this category.

2.4 Active and Passive Touch

The organization in terms of tactile, kinesthetic, and haptic perception adopted here recalls the distinction between active and passive touch emphasized by Gibson. Gibson especially took issue with the view that touch "sensations" can be understood as the building blocks of tactile perception. He believed that limiting the study of touch to examining the skin of a passive observer is a misleading idea supporting the sensation-based perception. Gibson, like Katz [10], felt the important phenomena of touch occurred when an observer was permitted to actively explore an object by touch. He drew some support for his opinion from the fact that when observers underwent passive tactile stimulation they tended to describe their experiences in terms of tactile sensations, whereas when they engaged in active tactile exploration they tended to describe their experience in terms of objects in space. Gibson believed that the process of touch undergoes a fundamental change when the observer is given control over the "pickup" of information. When permitted to examine an object actively, the observer does not attend to the

particular momentary sensations but rather seeks over time and space the invariances in the stimulation that characterize the object being explored.

Unquestionably, there is merit in Gibson's position, particularly with regard to the tactile perception of three-dimensional objects. It is unfortunate, however, that Gibson did not distinguish between active and passive touch in a consistent fashion. This has resulted in some confusion in the subsequent literature.

2.5 Phenomenology of Touch

The observations of David Katz have contributed much to our appreciation of the capabilities and richness of the sense of touch. There is a brief consideration of several phenomenological observations that occupied his interest. Katz [9] emphasized that most of our perceptual experience is of objects and events external to 'us' rather than of the more proximal stages and processes that intervene between the distal stimuli and our higher brain centers. However, there are numerous examples where "externalization of experience" occurs in spite of "subsidiary awareness of one or more intervening stages". Within touch, for example, the receptive surface of the skin, unlike that of the eye, is represented within perceptual space, yet frequently when the skin is touched the perceptual experience is of an object external to the perceptual boundary of the body. For example, when one probes a surface using a stylus held in the hand, one's awareness is not of the vibrations felt in the hand, but of the surface being explored. Similarly, when one stirs a viscous fluid, one has the experience of fluid at the end of the sting rod rather than of sensations in the fingers, joints, and muscles.

Katz observed that the senses vary in the degree to which the resulting percepts are experienced as part of the self (are "phenomenally subjective") or external to the self (are "phenomenally objective"). Vision is the most object-sided sense, for most visual experience is referred to perceptual space beyond the bodily self. At the opposite extreme are the interoceptive senses (hunger, thirst, etc.) and pain or the perceptual experience is of "sensations" within the phenomenal body. This distinction between the phenomenally subjective and phenomenally objective is purely a descriptive one. It is most useful in the

description of touch experience, for the sense of touch is intermediate between vision and the interoceptive senses in terms of how often perceptual experience is referred to either the subjective or objective poles. The objective pole is favored when the subject is allowed to explore an object actively and when the skin surface making contact with the object is that normally used for tactile exploration. Conversely, the subjective pole is favored when body loci such as the inside of the nose or ear are passively touched . Especially interesting are the situations where one part of the body touches another. If one part, like the fingertip, favors the objective pole while the second favors the subjective pole, the resultant touch impressions are referred primarily to the latter. If one part is moved across the surface of another, the objective pole dominates for the moving part and the subjective pole for the stationary part [11].

3. SOMATOSENSORY SYSTEM

The somatosensory system has generally been associated with the sense of touch. Neuroscientists use the term 'somatosensory' to refer to the neural system associated with the afferent fibers that constitute the somatic component of the peripheral nervous system. These fibers include the sensory components of the spinal nerves, which carry signals from the skin, muscles and joints..

3.1 Peripheral Mechanisms

The afferent neurons of the somatosensory system serve two functions: as receptors, and as devices for transmitting somatosensory information to the brain. Most of the receptive endings are located within the skin, which also serves as a medium for filtering mechanical information and as a source for chemical messengers that can communicate with certain types of neurons. The structure of the skin and its sensors, the mechanisms of sensory transduction, and the basis of coding in peripheral fibers are discussed in this section.

3.1.1 Skin

One of the more remarkable aspects of skin is its diversity. In some regions of the body it is covered by many small furrows, in others it's pulled tight and appears smooth. Another distinction is based on the presence of hair (hairy skin), or the absence of hair, which is called **glabrous skin**, meaning bare and smooth. Glabrous skin covers only a small part of the body such as the palm of the hand and the tips of the fingers. Glabrous skin is also thicker than hairy skin and it has a distinctive surface. Figure 3.1 compares the surface features of a section of glabrous and hairy skin. These ridges provide stability and are one of the reasons why the finger tips can resist a force that might cause a wrinkling of skin from other parts of the body.

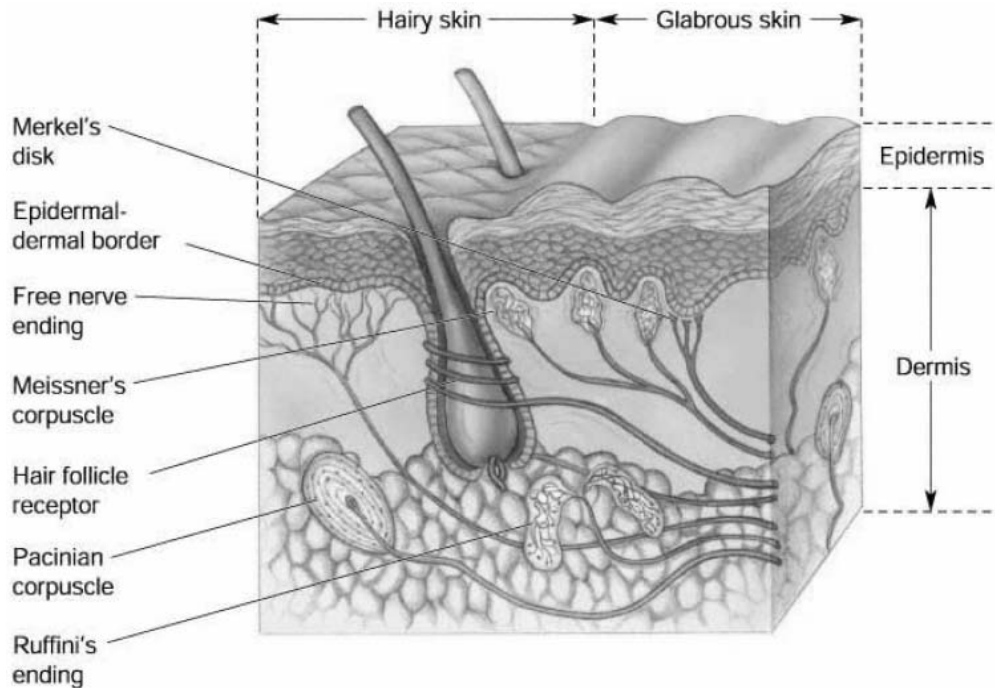


Figure 3.1 Skin.

3.1.1.1 Structure

Figure 3.1 shows a section through the skin. All skin consists of two embryologically distinct layers: an outer layer or epidermis and an inner layer called the dermis. Figure 3.1 also shows the subcutaneous tissue or hypodermis, bordering the dermis. The surface of the epidermis is called the corneum. It consists primarily of dead or 'keratinized' cell bodies that migrate away from lower region of the epidermis, which contains proliferative cells essential for the constant renewal of the skin

The dermis provides the skin much of its elasticity. It also includes a papillary layer, which forms an irregular border with the epidermis. The presence of the papillae of the dermis is responsible for the ridges and furrows on the skin's outer surface, such as those used in determining finger prints.

3.1.1.2 Innervation and Receptors

The neural innervation to the skin consists of both motor and sensory fibers, which form a complex intertwined network called a **fiber plexus** in the subcutaneous region. Many of the fibers undergo extensive further branching, leading to an additional plexus being formed at the base of the dermis.

Many of the motor fibers innervate blood vessels and play a role in controlling heat loss and heat gain. Some of the fibers branch and innervate sweat glands and hair cells located in the subcutaneous region. Evidence has also been provided of efferent fibers being able to control the sensitivity of skin mechanoreceptors [12] .

The sensory receptors associated with the skin are all extensions of sensory neurons with soma located either close to the spinal cord in dorsal root ganglia or in sensory nuclei of the cranial nerves in the central nervous system. The receptive terminals can be distinguished by the presence or absence of a surrounding capsule. **Free nerve endings** are the naked endings of the sensory fibers and are found to terminate at all levels of the skin. When such terminals are attached to specific non-neural cells or tissue they are called **epidermal endings**. One example of an epidermal ending is known as a **Merkel's disc**, which consists of a flattened nerve ending and a covering cell known as a Merkel cell. These are found at the base of the epidermis of glabrous skin.

A third kind of ending, an **encapsulated** ending, consist of one or more terminals surrounded by non neural cell. As illustrated in Figure 3.1, these come in a wide variety of forms:

1. **Meissner's corpuscles** consist of a complex configuration of two to seven nerve terminals covered by lamellae of Schwann cells. They are found within the surface layer (the papillae) of the dermis of glabrous skin.

2. **Ruffini's cylinders** are long structures with a center core innervated by a single myelinated axon. They are found in the dermis near the junction of the subcutaneous tissue in both glabrous and hairy skin.

3. *Krause end bulbs* are similar but somewhat smaller than Meissner's corpuscles and are found in mucocutaneous tissue, a part of the skin that includes the lips and external genitalia.

4. *Pacinian corpuscles* are the largest and most thoroughly studied of the end organs. They are oval shaped endings, approximately 0.5 mm in thickness and 1.5 mm in length, and are easily visible to the naked eye. They consist of an inner core surrounding the terminal of a single axon, a small subcapsular space, and an outer fluid-filled capsule. The inner core consists of approximately 60 concentric layers formed from lamellar cells, and the outer capsule has 20-30 cellular lamellae.

Encapsulated endings are also found outside of the skin. Joints, for example, contain Ruffini cylinders and structures called **paciniform corpuscles**, which are smaller but virtually identical in structure to Pacinian corpuscles.

One of the main reasons for suspecting that most somatosensory receptors are responsive to mechanical stimulation is that contact to the skin causes a transient mechanical distortion; skin is plastic, not rigid, and touch causes a change in shape. Transduction by mechanoreceptors can be considered as a three stage process that includes:

1. mechanical coupling, in which the mechanical response of the skin to the stimulus is transferred to the receptor;
2. deformation of the receptor producing an electrical signal, or generator potential;
3. transformation of a generator potential to neural firing.

Much of our knowledge about mechanoreceptor transduction is based on work done by W. Lowenstein on the Pacinian corpuscle [13].



Figure 3.2 Pacinian corpuscle.

3.1.2 Peripheral Coding

The response of somatosensory receptors is converted to cellular firing in afferent fibers, which transmit this information to the CNS. Each afferent fiber carries at least two kinds of information: localization and modality. Localization depends on the region of the body supplied by the fiber. Modality refers to the kind of experience, and compelling evidence exists for distinguishing between *touch, temperature, pain, and kinesthetic information*.

Within each modality additional information can be conveyed. Tactile information, for example, can be coded for intensity (pressure), texture, form, and vibration.

Peripheral fibers are distinguished based on fiber size and amount of myelination. Heavily myelinated fibers are classified as **A fibers**. The somatosensory system contains two kinds: **A delta** and **A beta**. A delta are small (1-5 microns), and are associated with temperature or pain. A beta are larger (5-20 microns) and are associated with tactile and kinesthetic qualities. There are also **B fibers** and they are similar to A delta, but are only associated with the autonomic nervous system. **C fibers** are small and unmyelinated and are thought to function in perception of pain and temperature [14].

3.1.2.1 Cutaneous Mechanoreceptor Channels and Functional Specificity

The peripheral afferent fibers responsible for tactile sensation are supplied by mechanoreceptive endings and provide the main source of information about tactile features. Four distinct types of mechanoreceptive units were uncovered, based on receptive field size and on the response to sustained stimulation. The current view is that each fiber type represents a separate tactile channel.

The four mechanoreceptive channels are referred to symbolically as RA1, RA2 (or PC), SA1, and SA2. RA stands for **rapidly adapting**, 'PC' is shorthand for Pacinian corpuscle, and SA represents **slowly adapting**. A rapidly adapting fiber is responsive to the onset of stimulation, is inactive during sustained stimulation, and fires again at the offset (removal of stimulation). Slowly adapting fibers, on the other hand, show sustained firing in response to a constant stimulus. The numbers refer to the size of the receptive fields, with '1' signifying small and '2' large.

RA1 channels : The RA1 fibers have small receptive fields and respond actively to an indentation of the skin but not to steady pressure. The optimal type of stimulus is vibratory pressure produced by rapid and repeated application and withdrawal of the stimulus. Estimation of the density of these receptors in an area of glabrous skin has been found to be equivalent to the number of Meisner's corpuscles. Consequently, the RA1 fibers are associated with Meisner's corpuscles.

RA2 channels : The second kind of fast adapting channel is associated with the Pacinian corpuscle and is the least common of the tactile channels. These channels have large receptive fields, show only a transient response to sustained mechanical stimulation, and are able to accurately respond to rapid vibration, at a frequency higher than the RA1 channels.

SA1 channels : As indicated by the label, these are fibers with small receptive fields, similar in diameter to those of the RA1 channels, but that show a sustained response to continuous pressure. These channels are thought to be associated with Merkel's cells.

Because this channel is responsive to sustained contact, it provides information about pressure. An important property of the SAI afferents is that they exhibit surround inhibition; pressure nearby inhibits an SA1 response. This feature may help with localization of contact.

SA2 channels : The primary difference between the SA2 and SA1 fibers is the size of the receptive field, with SA2 being much larger. SA2 fibers also can show directional sensitivity, responding best to stimulation moving in a particular direction. The SA2 channels have been associated with Ruffini's ending.

Intuitively, it seems likely that different mechanoreceptor channels represent specializations for detecting different aspects of tactile stimuli. Researchers have studied the response of the different mechanoreceptors to complex spatial stimuli [15] [16] .

3.1.2.2 Kinesthetic Mechanoreceptors

These include receptors associated with joints and those associated with the muscles. The joint receptors are typically encapsulated and present in joints or ligaments of the muscle. According to Darian-Smith [14], the joints have two major functional groups of mechanoreceptive endings: slowly adapting fibers and rapidly adapting fibers. The slowly adapting fibers reflect the activity of stretch-sensitive mechanoreceptors. The firing of joint receptors is now thought to reflect tension on the capsule encasing the receptor. The rapidly adapting fibers, on the other hand, respond only when the joint is being rotated.

The second kind of kinesthetic mechanoreceptor are receptors with muscles, which have been labeled **proprioceptors**, that provide the CNS with knowledge of muscle status. The muscle receptors are contained within two specialized organs, the *muscle spindles* and the *golgi tendon organ*. Both of these are responsive to stretch and play essential roles in regulating muscle length.

3.2 Central Somatosensory Pathways

Somatosensory signals are carried by sensory nerve fibers into the spinal cord, where they typically extend collaterals that may terminate locally, cross over to the contralateral side, or directly enter ascending fiber pathways.

3.2.1 Ascending Somatosensory Pathways

On entering the spinal cord, each dorsal rootlet splits into a medial and lateral division. These form the starting point of the ascending somatosensory pathways. The medial division is the start of the **medial lemniscus system**, while the fibers of the lateral division are associated with the **spinothalamic system**. The medial lemniscus system carries tactile and kinesthetic information from the spinal cord to the somatosensory cortex. The spinothalamic system is associated with temperature and pain.

3.2.1.1 The Medial Lemniscus System

The neural components of each ascending somatosensory system are customarily numbered on the basis of their synaptic proximity to the periphery. The term **first order neuron** is used to refer to the neurons constituting the peripheral nerve. The **second order neurons** are one synapse away from the periphery, and **third order neurons** are "twice removed".

A schematic illustration of the medial lemniscus system is shown in Figure 3.3. The system originates from the medial division of the spinal rootlets. On entering the spinal cord, the fibers can either project to the nucleus proprius (Laminae III, IV, and V) or course dorsally and rostrally to enter the **dorsal** funiculus. The funiculus is the spinal component of the medial lemniscus system; it contains two long pathways that are collectively known as the **dorsal column system**. These first order fibers consist of afferent *tactile and kinesthetic channels* discussed in the previous section and are one component of the dorsal column system.

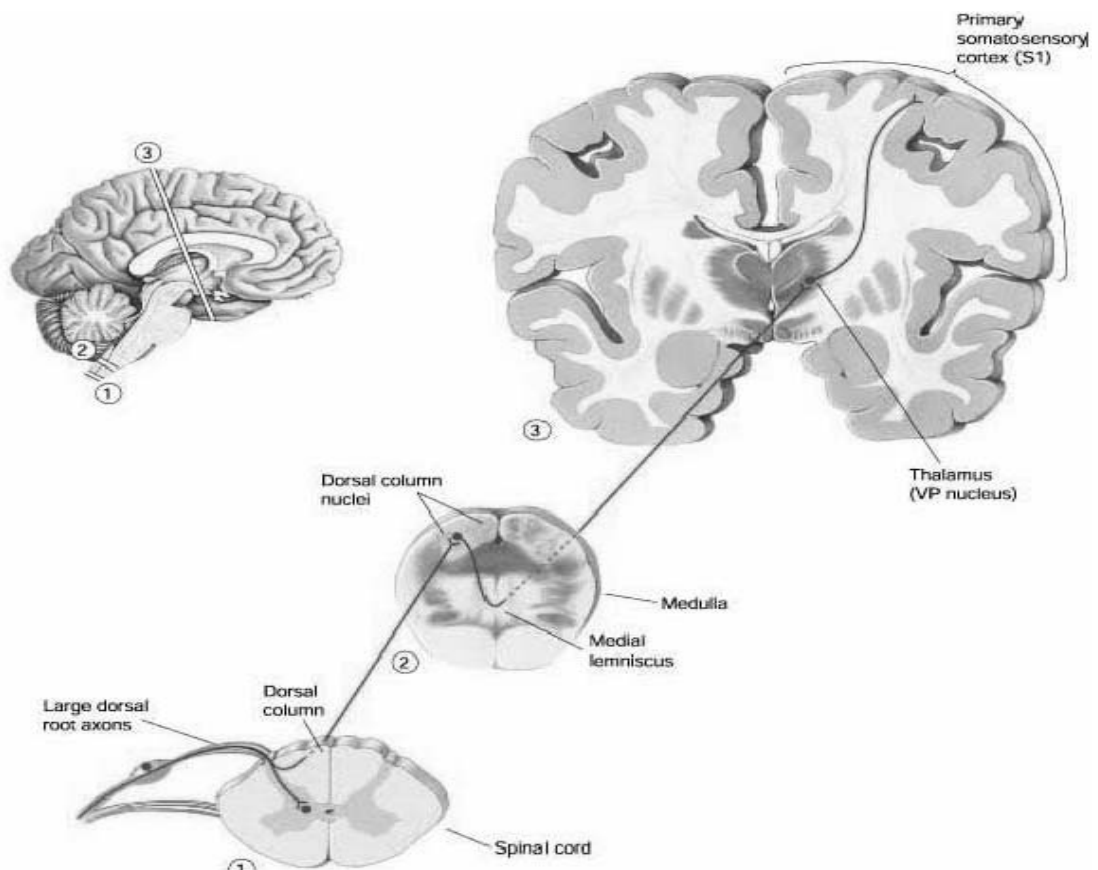


Figure 3.3 Medial lemniscus system.

A second component is the **postsynaptic dorsal column system**. This system arises from second order fibers that originate from the nucleus proprius. The second order fibers differ from the first in being responsive to either cutaneous or muscular afferents. It is assumed that this reflects convergence of first order afferents from both the skin and muscles onto second order afferents.

Dorsal columns consist of two long tracts, the **gracile tract** and the **cuneatus tract**, that carry tactile and kinesthetic information from the ipsilateral side of the body. When the fibers enter the dorsal columns, they enter laterally. Thus, fibers from the hindlimbs are located medially in the funiculus gracilis, while fibers from the forelimbs are located laterally in the funiculus cuneatus [17].

Although the organization at the point of entry is somatotopic, as the fibers ascend they appear to undergo some sorting based on the channel separation found in the periphery. Thus, anteriorly the gracile tract is composed almost entirely of rapidly adapting cutaneous afferents.

Unlike the other sensory systems, the ascending somatosensory fibers project to several different **thalamic nuclei**. The medial lemniscus system projects to two main targets, the ventroposterolateral nucleus (VPL) and the ventroposteromedial nucleus (VPM), which are part of a larger *ventroposterior complex* of nuclei.

The somatosensory thalamus maintains a somatotopic mapping of the body surface, with the region associated with the contralateral trunk and limbs (the spinal portion) projecting to VPL, while VPM receives axons from the face (the trigeminal portion). In addition to location specificity, thalamic cells also maintain the channel specificity seen in peripheral somatosensory fibers. Thus, some cells respond only to activation of RA1 fibers, and others respond only to SA1 fibers. Within the thalamus, each modality is represented by a set of cells that collectively maps the entire body surface. Within any given region of the thalamus, different channels are represented. As a result, the mapping of any single channel consists of a distributed set of discrete areas.

3.3 Cortical Processing

So far the mechanics of somatosensory sensation and coding in the PNS and CNS were discussed. The cortical organization and coding that results in somatosensory perception - our experience of somatosensory events would be discussed in this section.

3.3.1 Cortical Organization

Two, SI and SII, receive projections from the ventroposterior complex of the thalamus. The other two are located in the posterior parietal cortex and consist of areas 5 and 7, as identified by Brodman's cortical map. Recent developments have led to further

subdivisions of area SI, which is now divided into quarters, and area SII, which has been divided into halves.

3.3.1.1 Cortical Areas

Area S1 : The current four subdivisions of area SI in the primate are based on findings reported by Kaas [18], who identified four functional divisions referred to as 3a, 3b, 1, and 2. These numbers are based on the original cortical classification of Brodmann, and the location of each is shown in Figure 3.5.

Four separate rostrocaudal bands were described as illustrated in Figure 3.5. With respect to body representation, clear somatotopic maps of the contralateral body surface were found in areas 3b and 1, with the feet closest to the midline and the face most lateral.

The areas could also be distinguished by response properties. Area 3b and 1 were responsive to light touch; cells in area 3a required deep pressure, hard taps or body movement, which suggested that they were responding to muscle receptors. Thus, areas differ in the proportions of cells associated with specific kinds of channels and modalities [19].

Area SII is located in the ventrolateral region of the parietal cortex, adjacent to the lateral sulcus.

Posterior parietal areas (area 5 and area 7) are associated with somatosensory processing both contain cells responsive to tactile input. Area 5 is immediately posterior to area 2. The receptive fields of area 5 cells are can be distinguished by their size, which represent larger areas of the body surface than the cells of SI. Another distinctive feature of the area 5 cells is their responsiveness to particular movements.

Area 7a, is an endpoint of a spatial processing system. Area 7 also contains a more lateral region, area 7b. Extracellular recordings from both 7a and 7b have revealed cells that are responsive to somatosensory stimuli. Because area 7 is responsive to sensory input

from more than one modality (e.g., visual stimuli as well as somatosensory) area 7 is considered to be a multimodal site.

Both the insula and area 4, the frontal cortex region immediately anterior to area 3a, have also been linked to the somatosensory system. The insula is an anatomical target of area SII and appears to be important establishing associations that involve *tactile information*. Pons [20] found monkeys with lesions to the insula to be severely impaired on a test of tactile memory. The deficit was specific to touch, and no impairment was observed in a visual memory test.

Area 4 of the frontal cortex is densely supplied with somatosensory input, and has an associated somatotopic map. Area 4 is known as primary motor cortex. Some researchers refer to area 4 as sensorimotor cortex.

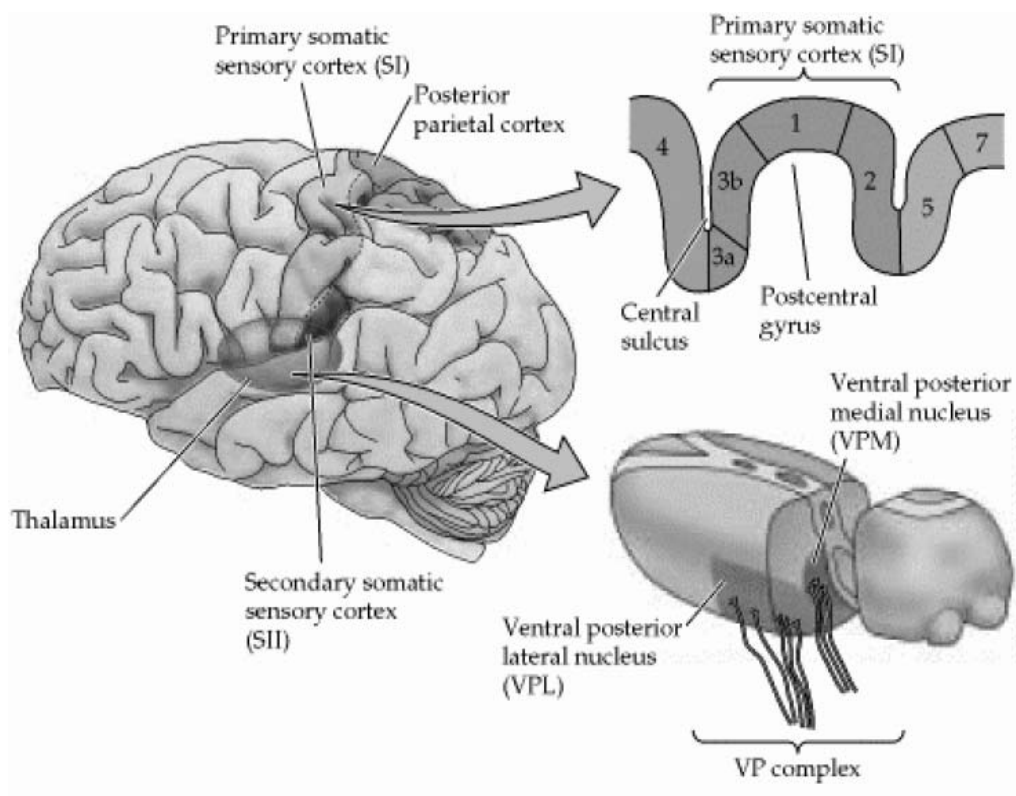


Figure 3.5 The Somatosensory Cortex.

3.3.3 Functional Organization

Not enough is known about somatosensory processing to justify an exhaustive functional analysis. Accordingly, only two kinds of somatosensory processing will be considered: tactile feature perception, and haptic processing.

3.3.3.1 Tactile Feature Perception

In humans, damage to primary somatosensory cortex is associated with deficits in somatosensory discrimination. These deficits affect two-point discrimination and recognition or localization of touch. Additionally, damage may cause **astereognosis**. While identification may no longer be possible, the subject is aware of having contacted the object.

Experimental work with non human primates suggest an even finer functional resolution can be made. Using discrimination learning procedures, selective damage to area 2 was found to disrupt size and shape discrimination; damage to area 1 affected texture discrimination; and area 3b lesions impaired all tactile discrimination [21].

Area SII is also important in tactile feature recognition, as damage to SII produces severe and long lasting deficits in tactile discrimination. Thus, normal tactile processing appears to depend on the ventrolateral processing stream.

3.3.3.2 Haptic Processing

Haptic processing depends upon movement and touch being combined. Cells that require both exist in areas 3b and 1. A population of neurons was found that showed discharge only during active movement of the fingers, usually in a specific direction [22]. These cells also showed differential sensitivity, being maximally responsive to particular surface patterns. Preliminary analysis of cells in area 2 showed a more complex relationship to movement. Some cells, for example, were only activated by brushing of two or more adjacent finger pads. These findings suggest that haptic processing proceeds in a serial fashion in SI.

Haptic processing beyond SI occurs in areas 5 and 7. Numerous studies have confirmed that cells in area 5 are responsive to both movement and touch. In area SI haptic processing can be accounted for by somatosensory activation of RA1 fibers, which fire in response to movement over textured surface. Area 5 and 7 cells, however, are responsive to larger movements like those of a limb. These findings raise the possibility of the posterior parietal cortex being involved in the integration of tactile perception with movement [23].

4. COGNITIVE TACTILE PROCESSES

There are different suggestions in the literature about higher cognitive processes involved in processing of sequential tactile stimuli. Heller [24] suggested that recall for a sequence of tactile stimuli does not reflect “higher cognitive activities” but instead is dependent on adequate sensory perception. However, in another study [25] the results shown are inconsistent with Heller’s suggestion. The retention of tactile sequence is different from that of a single tactile stimuli. Whereas a discrete tactile stimulus may reside within a modality-specific sensory store, a sequence of tactile stimuli exceeds such store’s capacity and therefore can be retained only through attention-demanding and vulnerable recoding processes. There are several models of human information processing in the literature. These models are mainly based on the studies which examine visual and auditory modalities. However, little is known about the cognitive mechanisms operating *solely within the tactile modality*.

4.1 Information Processing Model

The model of human information processing consists of three elements. These are: perception, attention, and memory. Tactile perception is discussed in detail in the previous sections. The other aspects of the human information processing is going to be explained in this section.

The basic structural features of the system are three memory stores, which are called the *sensory memory*, *short-term memory* and *long-term memory* [26]. Figure 4.1 represents a schematic view of the system; the three major memories of information are represented as boxes, whereas the arrows represent the flow of information from one memory to another. Long-term memory will be out of question in this study; because learning, as the process by which the information from short-term memory is transferred to long-term memory is not involved here. The item first enters the system via one of the sense organs, for example, the eyes or skin. It is then received by sensory memory, a memory which holds a nearly literal record of the sensory image. In other words, this memory accepts all sensory information in a fairly complete form, but it does not hold that

information for very long. Rather, information decays quickly, in most cases in less than a second or so. However, information may be preserved for longer than a second by quickly transferring it to another memory, short-term memory.

Short-term memory is really a working memory, a place where conscious mental processes are performed [27]. It has several major characteristics. First, it is of limited capacity, that is, it cannot hold very much information simultaneously. Evidence suggest that we can hold in short-term memory only something on the order of 7 (plus or minus 2) items of information at any given time. Second, information from this memory will decay and be gone completely within about 15 seconds. Thus, short-term memory is easily overtaxed and is generally thought to admit only those items to which we strictly *attend*. Attention is an important process that is going to be considered in this task. In addition, a continual flow of information to short-term memory necessitates that some items will be replaced by incoming items. We can only focus on, concentrate on, or be conscious of a few things at once. Attention seems to require active, conscious processing, and we are limited in our capacity for attentional processing . Moreover, we seem to be limited in our capacity to attend simultaneously to more than one task. Thus attention is associated with the conscious, active processing required whenever we perceive some event and then remember it later on.

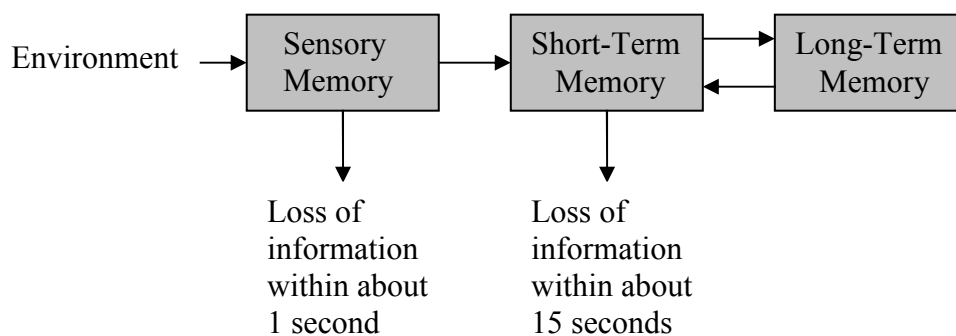


Figure 4.1 Schematic representation of human information processing system.

Vigilance, distribution, and selection are all functional aspects of attention, but they are not independent of each other. All these attributes of attention were considered before designing the psychophysics experiment so that all the subjects have similar conditions for

attention. In a previous study, an interaction between visual orienting and tactile attention is clearly demonstrated, illustrating that visual orienting to a body site is sufficient to facilitate the focusing and maintenance of attention at that site [28].

4.2 Tactile Short-Term Memory

In recent years much progress has been made in our understanding of the relationship between short-term memory and tactile sensory storage. Most of the evidence in the auditory modality relies heavily on the serial recall paradigm. Typically, recall of the last item in a to-be-recalled sequence is superior. The superior recall of the final item (known as recency) is taken to reflect the action of a specialised tactile sensory store. Watkins and Watkins [29] presented a to-be-recalled sequence of tactile stimuli to the fingers. The four fingers of both hands were each touched once in a sequence, and the fingers were numbered from 1 through to 8 from the left. Although recall of pre-terminal list items reflects the use of verbal recording and rehearsal mechanisms (precisely as with an auditorily presented list), a recency effect points to the existence of a nonverbal, tactile sensory store. The tactile sequences were followed by either an acoustic (control) or a tactile (suffix) recall signal. Recall curves for both types of sequence showed similar primacy effects, but recency was present in the control condition only.

Using a rather different paradigm, Gilson and Baddeley [30] required subjects to identify the location of a discrete tactile stimulus applied to the underside of the forearm after delays ranging from 0 to 60 seconds. During the retention intervals subjects were either quiet or performed a concurrent simple arithmetic task (an articulatory suppression condition). In particular, for Gilson and Baddeley the detrimental effect of articulatory suppression on recall accuracy was only apparent after a 15-second retention period. This finding led the authors to propose that tactile short-term memory comprises two processes: a fading sensory memory which is resistant to a secondary task, and a more stable memory system which appears to rely on a form of obscure, non-verbal, tactile rehearsal, although the precise nature of such tactile rehearsal is not discussed.

5. METHODS

5.1 Subjects

Five female and five male university students have been used as subjects in the experiments. The mean age of the subjects was 23 (range: 19-27). 9 subjects declared they were right-handed; one subject declared he was left-handed. The experiments do not pose any harm and they adhere to the US National Institutes of Health ethical guidelines for testing human subjects. The subjects were university students recruited locally and they gave written consents. None of the subjects had dermatological or neurological problems that could interfere with the tactile experiments. The tactile stimuli were applied on the right or left index finger tips of the subjects according to handedness.

5.2 Materials

Three smooth one meter sticks, each of them covered with different number of small nails (8,10,12) were used as surfaces to be scanned by touch.



Figure 5.1 One meter stick covered with small nails.

Each nail head was a tactile stimulus to be applied on the finger tip, and the inter-stimulus distance varied between 1 cm and 13 cm. Scanning a finger tip across the stick (or vice versa) sequentially presented supra-threshold tactile stimuli to each subject.

As the velocity is crucial in the experiments, electronic devices were designed to determine scan durations. One of the devices detects the start and end of the scan by using skin conductance properties.

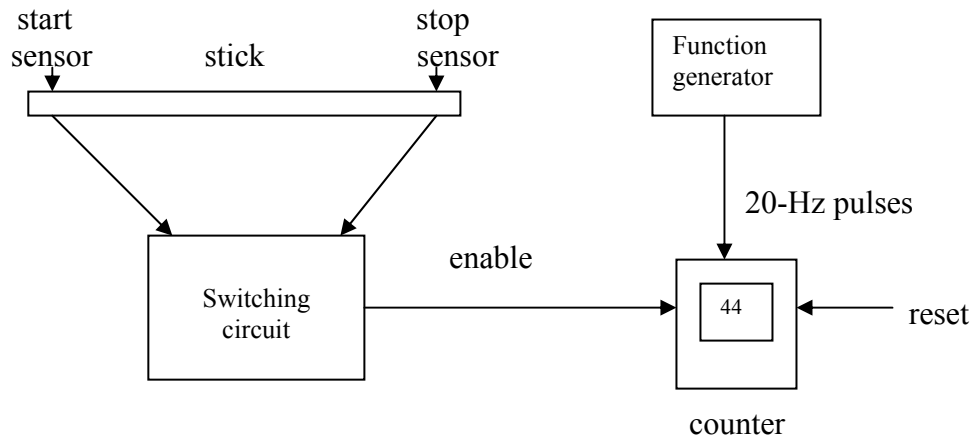


Figure 5.2 Block diagram of the apparatus.

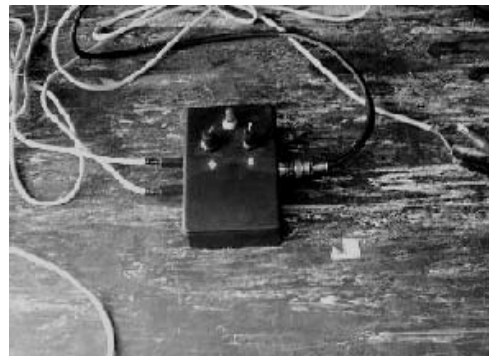


Figure 5.3 Device designed to detect start/end of scan (enable circuit).

The other device is a simple digital counter. It counts the number of pulses generated throughout tactile scanning. The pulses are generated by a function generator.

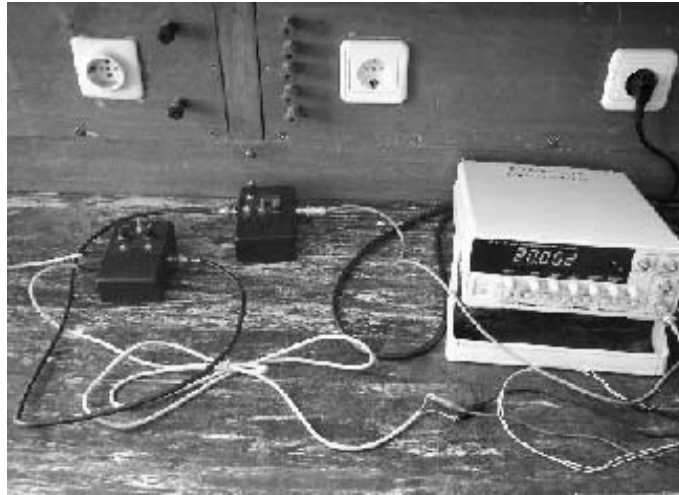


Figure 5.3 Enable circuit ,digital counter, and the function generator.

The average tactile speed is calculated by dividing the length of the stick to the scan duration. The duration of scan is the number on the counter, which is the number of pulses generated throughout the scan, divided by the frequency generated by the function generator ($f = 20$ Hz). During the scanning, the finger tip did not touch the sensors. Therefore, the counter was enabled and it counted the pulses generated by a function generator. Before the scanning started and after it ended, the finger contacted one of the sensors and disabled the counting. The counter was reset before each scan and the total pulses counted after each scan was read off the counter. The scanning distance was 1 m. Therefore, the average scanning speed (v) could be calculated as

$$v = \frac{\text{distance}}{\text{time}} = \frac{1}{n \cdot \frac{1}{20}} = \frac{20}{n} \quad [\text{m/s}] \quad (5.1)$$

where n is the number of pulses counted.

5.3 Procedure

The experiment was divided into two main parts. In the first part of the experiment each subject scanned the sticks actively. They sat down on a chair and sticks were fixed on a table in front of them. Sticks, which have different number of nails on each, were

changed randomly at each trial in order to decrease the chance of memorization by the subject.



Figure 5.4 Experimental setup for active touch.

Each subject scanned the sticks actively both *while their eyes were open* and *while they were closed*. So, the effect of vision on the accuracy of detection was tested by this way. The subjects were instructed to maintain a moderate contact force with the stick surface. The contact force was not measured, but the nail heads were large enough to be detected in every experimental condition. The tactile stimuli (i.e. nails) were always hidden from the view of the subject by a piece of paper taped on the subject's hand, but the subjects could gaze at their finger tips in the 'eyes open' condition.

Subjects were trained for smooth scanning by some preliminary trials, specially when their eyes were closed, by the help of the experimenter.



Figure 5.6 Active touch.

In each case (when the eyes are open/closed) subjects scanned the surface of the three sticks both from left to right and from right to left and counted the number of nails they have detected while scanning by their index finger at four different velocity ranges:

- | | | |
|----|------------------|-------------------|
| 1. | fast (F) | (0.75 – 1.00 m/s) |
| 2. | medium fast (MF) | (0.50 – 0.75 m/s) |
| 3. | medium slow (MS) | (0.25 – 0.50 m/s) |
| 4. | slow (S) | (0 – 0.25 m/s) |

Before the experiment, each subject was trained to scan their fingers at the speed categories given above. Each subject was tested for four trials (two from left to right and two from right to left) at each of the four velocity ranges. Although the scanning speed could not be very accurately controlled, it was accurately monitored and only data obtained with valid scanning speeds were analyzed. The four coarse categories of scanning speeds are adequate for the purpose of this study.

In the second part of the experiment, the subjects scanned the sticks passively. Another apparatus was designed for this part of the experiment. It was such a design that the sticks could slide over on it smoothly. The experimenter also had previous training for passive touch experiments.

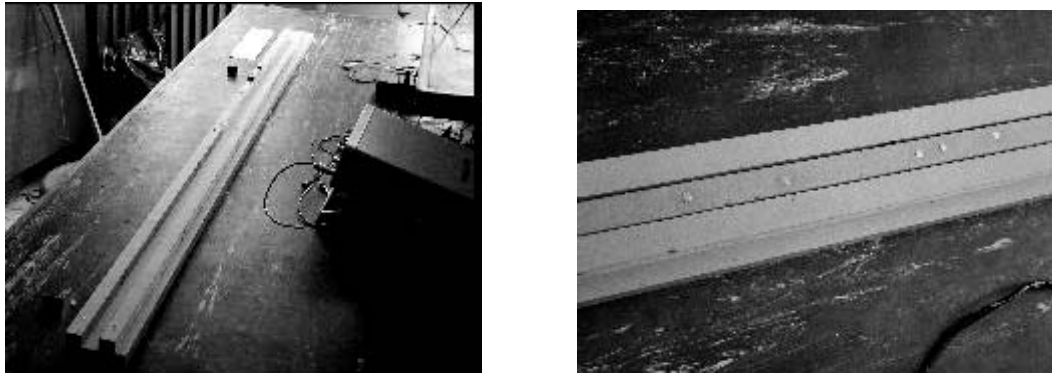


Figure 5.7 Apparatus designed for passive touch.

The index finger was fixed on the apparatus by a cellulose tape just above the sticks so that the touch was perfectly passive.

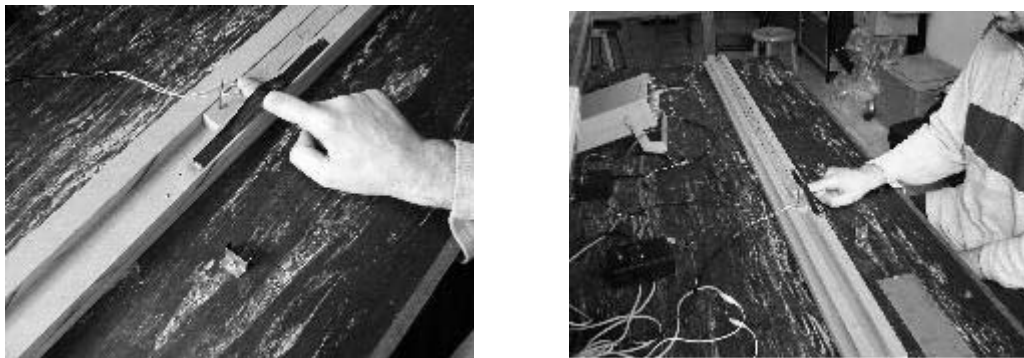


Figure 5.8 Index finger fixed on the apparatus.

Sticks were pulled horizontally below the finger as it maintained contact with the finger. All three sticks were pulled at the same range of velocities again for both the eyes open and the eyes closed cases.



Figure 5.9 Passive touch.

For the ‘eyes open’ condition, the subjects were instructed to orient visual attention to their finger tips, which they could see moving. For the ‘eyes closed’ condition, the subjects were blindfolded and instructed to face away from the experimental setup. The subjects were expected to recall the number of tactile stimuli immediately after scanning.

Each trial began when the subject placed the finger tip on the start sensor. Then, the experimenter reset the counter and gave a start signal to initiate the scanning. After the scan, the subject recalled the number of presented stimuli while holding the finger on the end sensor. The trial finished by recording the subject response and the counter display. At total, each subject was tested for 96 trials ($4 \times 4 \times 3 \times 2$) actively and 96 trials passively. Each experimental session took 1-2 hours with breaks in between. Intertrial intervals (1-2 minute) were given between each trial and a ten minute break was given after half of the trials were completed. The order of testing active/passive scanning, and that of the eyes closed/eyes open conditions were randomized during the experiments. The experiments were completed in 10 sessions.

6. ANALYSIS AND RESULTS

6.1 Analysis

For each experimental condition, four responses were obtained from each subject. These estimates for the number of presented stimuli were averaged. The average estimation error was normalized with respect to the actual number of stimuli to yield the relative error.

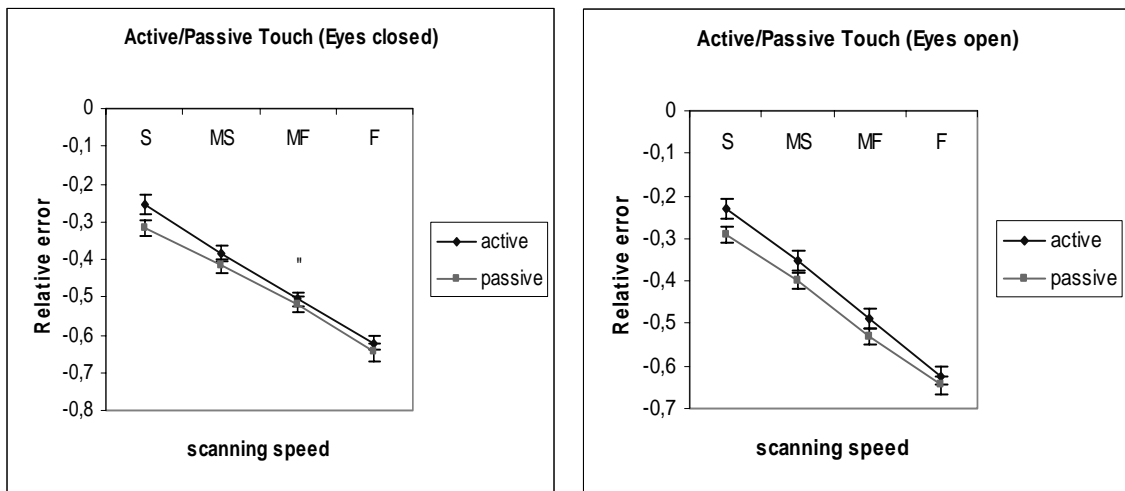
First, the average relative errors were analyzed separately for each combination of the presentation mode and the status of visual attention. The correlation between the scanning speed and the relative error was found. Then, the effects of the presentation mode and the status of visual attention were studied by using 3-way ANOVA with 10 replications. No interactions were found between the variables (Table 6.1). So, the data were successively pooled over every combination of two factors to show the main effect due to the third factor. The statistical analyses were performed in MATLAB. The error bars in the plots are the standard errors of the mean.

6.2 Results

Active and passive touch were compared at each scanning speed for both eyes closed and eyes open condition (Figure 6.1). The actual scanning speeds of the subjects during the experiments at each speed range were recorded in between:

- 1- 0.79 m/s – 0.94 m/s (Fast)
- 2- 0.50 m/s – 0.63 m/s (Medium Fast)
- 3- 0.32 m/s – 0.39 m/s (Medium Slow)
- 4- 0.21 m/s – 0.23 m/s (Slow)

Relative errors made at three sticks were averaged at each scanning speed. The difference between active and passive touch is more obvious at the slowest scanning speed.

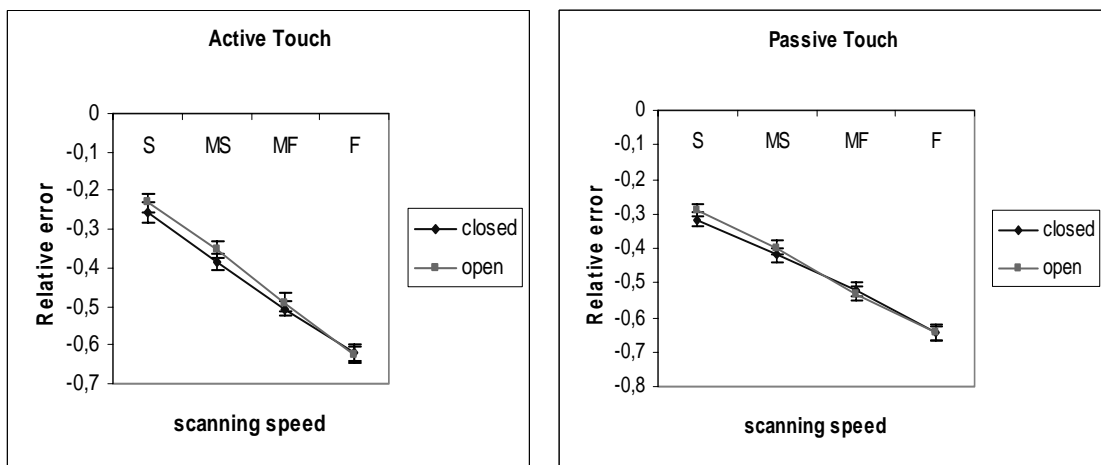


(a)

(b)

Figure 6.1 Relative errors at each scanning speed in active and passive touch. (a) eyes closed, (b) eyes open. S- Slow, MS- Medium Slow, MF- Medium Fast, and F- Fast.

The effect of visual attention on the accuracy was compared at each scanning speed in both active and passive touch (Figure 6.2). There is no significant effect observed.



(a)

(b)

Figure 6.2 Relative errors in eyes open and eyes closed condition (a) active touch, (b) passive touch. S- Slow, MS- Medium Slow, MF- Medium Fast, and F- Fast.

According to the ANOVA, there is a significant main effect of the presentation mode. Therefore, active and passive touch produces statistically different results in the sequential processing task. According to the ANOVA, there is no significant effect of orienting the visual attention to the tactile task.

Table 6.1
3-way ANOVA results.

Source	Sum of Sq.	d.f.	Mean Sq.	F	p-value
Speed	2.9019	3	0.9673	107.5	<0.001
Mode	0.0575	1	0.0575	6.39	0.0126
Visual	0.0068	1	0.0068	0.76	0.3861
speed × mode	0.0085	3	0.0028	0.31	0.8154
speed × visual	0.0058	3	0.0019	0.21	0.8862
mode × visual	0.0008	1	0.0008	0.08	0.7727
speed × mode × visual	0.0013	3	0.00044	0.05	0.9854
Error	1.29573	144	0.009		
Total	4.2782	159			

Because there are no interactions between any combinations of the variables, the relative errors can be plotted as a function of each independent variable (Figure 6.3). The relative errors for active touch are less than the relative errors for passive touch (pooled $n = 240$; t-test, $p = 0.010$). The average pooled relative error is -0.433 with active touch and -0.471 with passive touch. There is no significant difference between relative errors in cases where eyes are closed and eyes are open (pooled $n = 240$, t-test, $p = 0.428$).

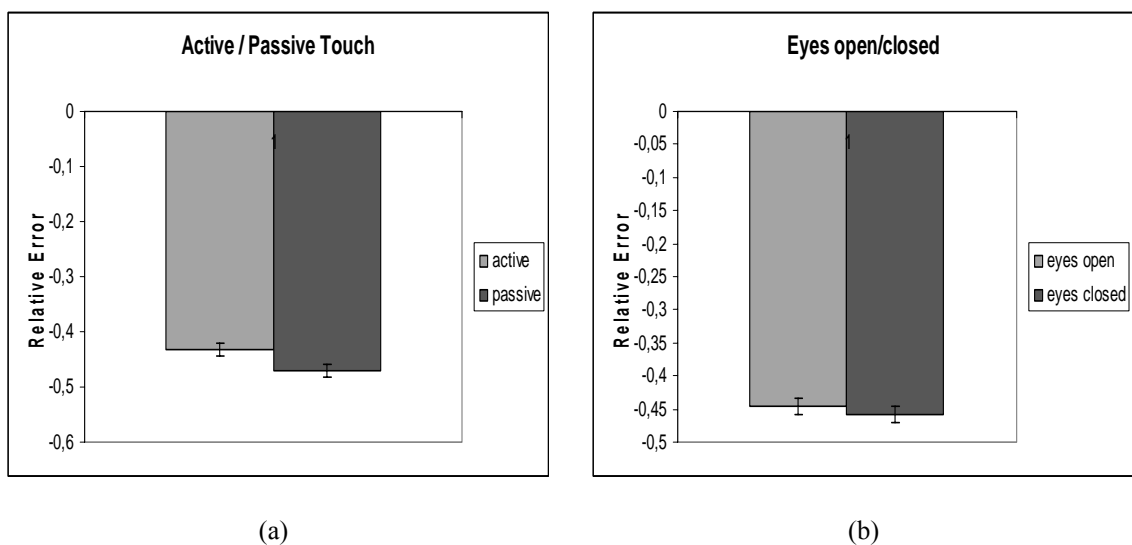


Figure 6.3 Relative errors for pooled data: (a) active vs passive touch, (b) eyes open vs eyes closed.

The relative errors were plotted as a function of the scanning speed (Figure 6.4). The relative errors increase (more negative) as the scanning speed increases (-0.273, -0.389, -0.512, -0.634 respectively).

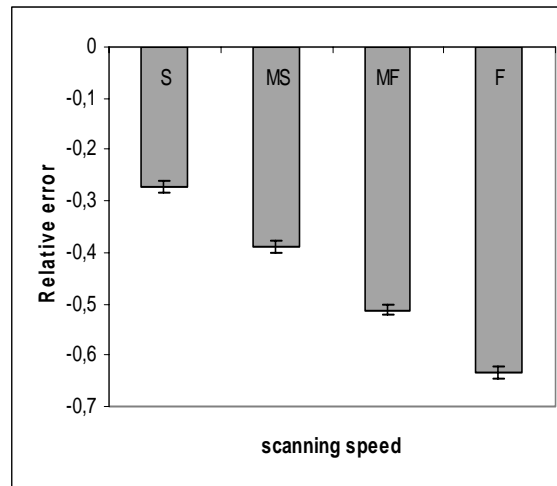


Figure 6.4 Relative errors as a function of scanning speed.

Data for female subjects and the data for male subjects were analyzed separately in order to examine gender differences in this task. The relative errors for active touch were compared to the relative errors for passive touch in females and males separately (Figure 6.5). The difference is not statistically significant in female subjects (pooled $n = 120$; t-test, $p = 0.466$). However, the difference is significant in the case of male subjects (pooled $n = 120$; t-test, $p = 0.011$).

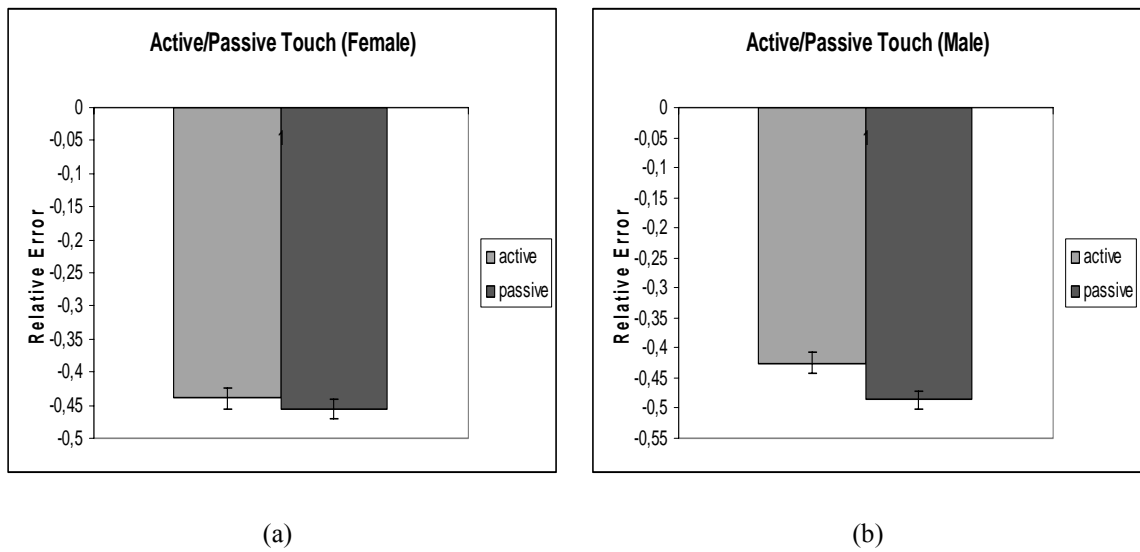


Figure 6.5 Relative errors for active and passive touch in (a) female subjects , (b) male subjects.

The relative errors of female and male subjects in active touch were compared (Figure 6.6). The difference is not statistically significant (pooled $n = 120$; t-test, $p = 0.577$) in active touch. The relative errors of female and male subjects in passive touch were also compared. The difference is not statistically significant (pooled $n = 120$; t-test, $p = 0.155$) also in the passive touch.

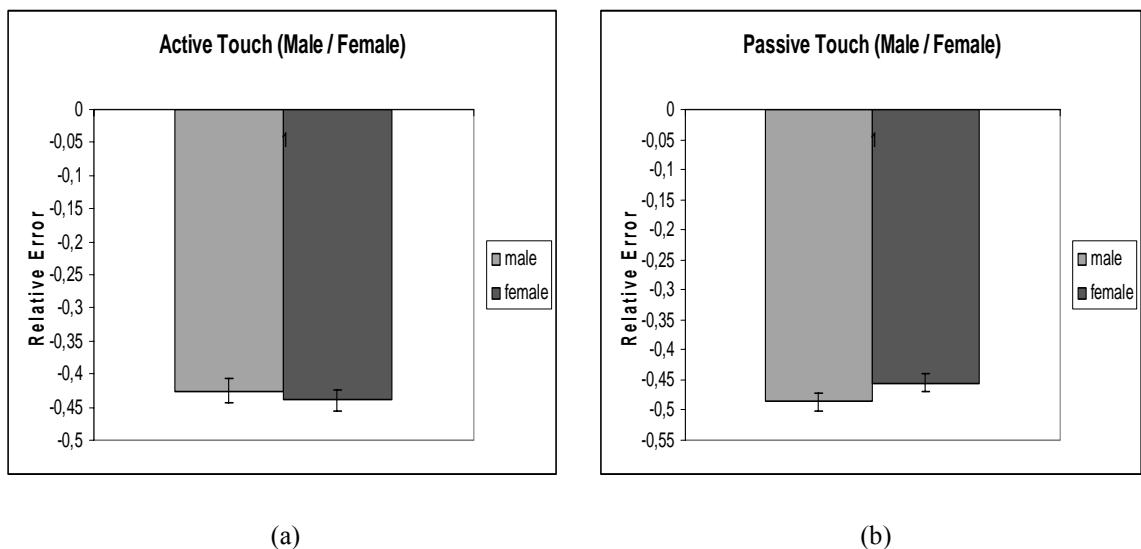


Figure 6.6 Relative errors of male and female subjects in (a) active touch , (b) passive touch.

Some post-hoc analysis of the distribution of the tactile stimuli on the scanning surfaces was done and revealed the following (not necessarily consecutive) inter-stimulus distances: 2, 3, 6, 7, 9, 13, and 13 cm for the 8-item stick; 1, 2, 5, 5, 7, 7, 9, 11, and 12 cm for the 10-item stick; 1, 2, 2, 4, 5, 5, 5, 6, 8, 9, and 10 for the 12-item stick. The 30-ms minimum inter-stimulus interval would impose the following maximum counts for S, MS, MF, and F average scanning speeds respectively: 8, 8, 8, and 7 for the 8-item stick; 10, 9, 9, and 8 for the 10-item stick; 12, 11, 11, and 9 for the 12-item stick. These correspond to the relative errors: 0, 0, 0, and -0.125 for the 8-item stick; 0, -0.100, -0.100, and -0.200 for the 10-item stick; 0, -0.083, -0.083, and -0.250 for the 12-item stick. The actual relative errors are -0.172, -0.300, -0.448, -0.583 for the 8-item stick; 0.303, -0.405, -0.521, -0.644 for the 10-item stick; -0.345, -0.462, -0.567, -0.674 for the 12-item stick. These values are much higher than the average relative errors caused by the limitation of the minimum inter-stimulus interval.

7. DISCUSSION

According to the results there is a statistically significant difference between active and passive touch. However, this difference is so small in numerical terms and it does not reflect an influence of presentation mode on the performance in the counting task. Lederman [3] obtained similar results in a task of detecting surface roughness and Vega-Bermudez and K.O. Johnson [4] in tactile feature extraction. It was concluded that active touch does not improve performance if the stimulus is applied only at finger according to these studies. Different kinds of processing of tactile input (temporal/spatial) are involved in these studies. So, ‘the stimulus configuration’ may actually be responsible for the similar results obtained for active and passive touch unrelated to the sequential processing system. The configuration adopted for this study was necessary to control the presentation timing of the stimuli. However, in another study tactile stimuli were sequentially presented to ‘different locations of the hand’ in order to simulate a shape recognition task which resulted in a considerable difference between active and passive touch [31].

It is important to note that psychophysical systems which are linked to the glabrous and hairy skin act differently during the passive reception of sensory information [11]. When one is touching himself/herself (i.e. intra-active touch), the passive side contributes significantly to the perception. Intra-active magnitude estimation produces different results than passive estimation on hairy skin, but similar results with passive estimation on glabrous skin. In the experiments presented here, only glabrous skin was stimulated, because tactile exploration is mainly done by the glabrous skin. However, it would be interesting to repeat the experiments by using a hairy skin site, e.g. back of a finger or back of a hand, to investigate the effects of active and passive scanning.

As mentioned in the introduction, there exist two hypothesized theories of sequential processing: feature specific and central timing theory [8]. The results in this study could not be confirmed by the central timing theory as the relative errors shown in Figure 6.3 are higher than the relative errors caused by the limitation of the minimum inter-stimulus interval.

This suggests a significant contribution of feature-specific sequential processing mechanisms and/or the involvement of higher cognitive processes such as burden on short-term memory. However, active detection of the tactile stimuli does not significantly improve the performance either. This result contradicts with the assumption given in the introduction, that a feature-specific mechanism may be enhanced by the additional sensory inputs, activation of the motor system and the executive functions. It is not possible to evaluate this at the moment. It needs further investigation specially on short-term memory.

Miles and Borthwick [32] found that recall accuracy in a tactile task is impaired both by articulatory suppression and tactile interference. It was, therefore, concluded that articulatory suppression should operate on a separate mechanism, perhaps by depleting some central-processing resources. Since, the main goal of this study is not to study tactile memory mechanisms, articulatory suppression is not applied here. However, sequential presentation of the tactile stimuli may cause interference in the short-term memory and reduce recall accuracy in the counting task. It may be expected that more stimuli can cause more interference, and thus, reduce the performance. Moreover, the capacity of the tactile short-term memory is limited as mentioned in the previous sections and is reduced with higher presentation rates [25]. The relative errors increase as the scanning speed increases as shown in Figure 6.3. Therefore the capacity of the short-term memory may be hypothesized to be gradually reduced as a function of the presentation rate. This could be tested in another study.

No visual-attention effects could be found in this study as shown in Figure 6.2. These results contradicted to the results of Llyod [28] illustrating that visual orienting to a body site is sufficient to facilitate detection of tactile stimuli. The measure of accuracy of the detection was reaction time, but relative errors were used as the measure in this study. In addition, different kinds of tactile signals were applied to the skin. The effect of different stimuli types and configurations on the performance could be tested. In their study, Lloyd targeted the basic processing by tactile psychophysical channels [33], which are directly mediated by four mechanoreceptive systems. A counting task, however, involves a much higher-level of neural processing and the slight differences due to visual effects may be irrelevant in the related cognitive processes. Moreover, orienting visual attention has just the opposite effect on the sense of touch in certain tasks. For example, attentional blink

refers to the temporary reduction in the ability to identify or detect the second target after selecting the first target. Soto-Faraco [34] showed that a crossmodal attentional blink occurs between visual and tactile stimuli when one precedes the other randomly. Therefore, attending to a visual target may prevent the selection of a subsequent tactile target. More studies are necessary to explain the modulatory effects of vision on the tactile sense.

Active and passive processing of sequential tactile inputs was compared in female and male subjects separately. Results of the comparison made in the female subjects illustrated that the difference is not statistically significant. However, the difference is statistically significant in the case of male subjects. Besides, female subjects were compared with the male subjects in active touch and in passive touch separately. The differences are not statistically significant both in active and in passive touch. As the number of test subjects was small, it is difficult to draw meaningful conclusions about the gender differences in the task.

There was no interaction between the three variables considered (presentation mode presentation rate, and visual attention). The results presented here may be helpful for designing future studies which investigate each variable in simpler tasks and studies investigating the higher cognitive mechanisms in the counting task and memory mechanisms involved in the task and interactions of these with the lower-level tactile perception mechanisms. Active touch could be compared with the passive touch in a texture discrimination task where surface is modified throughout the scan. Visual attention could be tested in a pattern recognition task where the subject is asked to detect a familiar pattern among different patterns. In this case the reaction time (RT) would be measured instead of the accuracy. The effect of speed could be analyzed in a similar task mentioned above, but the stimulus is applied with different inter-stimulus intervals.

REFERENCES

1. James J. Gibson. "Observations on active touch". *Psychological Review*, Vol. 69, No. 6, November 1962.
2. Von Holst, E. "Relations between the central nervous system and the peripheral organs". *British Journal of Animal Behavior*, 2, pp. 89-94, 1954.
3. Lederman, S.J. "The perception of surface roughness by active and passive touch". *Bulletin of the Psychonomic Society*, 18(5), pp. 253-255, 1981.
4. F. Vega-Bermudez, K. O. Johnson and S. S. Hsiao. "Human tactile pattern recognition: active versus passive touch, velocity effects, and patterns of confusion". *Journal of Neurophysiology*, 65: pp. 531-546, 1991.
5. Pöppel, E. "A hierarchical model of temporal perception". *Trends in Cognitive Sciences*, 1, pp. 56-61, 1997.
6. Hirsh, I. J., & Sherrick, C. E. "Perceived order in different sense modalities". *The Journal of Experimental Psychology*, 62, pp. 423-432, 1961.
7. Kanabus, M., Szeląg, E., Rojek, E., & Pöppel, E. "Temporal order judgement for auditory and visual stimuli". *Acta Neurobiologiae Experimentalis*, 62, pp. 263-270, 2002.
8. Fink, M., Ulbrich, P., Churan, J., & Wittmann, M. "Stimulus-dependent processing of temporal order". *Behavioral Processes*, 71, pp. 344-352, 2006.
9. James C. Craig, Gary B. Rollman. "Somesthesia". *Annual Review of Psychology*, 50, pp. 305-31, 1999.
10. Krueger, L. E. "David Katz's *Der Aufbau der Taatwelt*: A synopsis". *Perception and Psychophysics*, 7, pp. 337-341, 1970.
11. S.J. Bolanowski, R.T. Verrillo, Francis McGlone. "Passive, active and intra-active (self) touch". *Behavioural Brain Research*, 148, pp. 41-45, 2004.
12. Mountcastle, V. Mechanoreceptive sensibility. In: *Handbook of Physiology. III Sensory Processes, Part 2*. pp. 789-878, 1984.
13. W.R. Loewenstein and R. Skalak, "Mechanical transmission in a Pacinian corpuscle". An analysis and a theory. *Journal of Physiology*; 182(2): pp. 346-378, 1966.
14. Darian-Smith, "The sense of touch: performance and peripheral neural processes". *Handbook of Physiology. III Sensory Processes, Part 2*. pp. 739-788, 1984.
15. Johnson, K.O., & Hsiao, S.S. "Neural mechanisms of tactual form and texture perception". *Annual Review of Neuroscience*, 15, pp. 227-250, 1992.
16. Johnson, K.O., & Lamb, G.D. "Neural mechanisms of spatial tactile discrimination: neural patterns evoked by Braille-like dot patterns in the monkey". *Journal of Physiology*, 310, pp. 117-144, 1981.

17. William F. Ganong. *Review of Medical Physiology*, 24, pp. 139 – 143, 2003.
18. Kaas, J.H., Nelson, R.J., Sur, M., Lin, C., & Merzenich, M.M., “Multiple representation of the body within the primary somatosensory cortex of primates”. *Science*, 204, pp. 521-523, 1979.
19. Krubitzer, L., Clarey, J., Tweedale, R., Elston, G., & Calford, M., “A redefinition of somatosensory areas in the lateral sulcus of Macaque monkeys”. *Journal of Neuroscience*, 1995, 15, pp. 3821-3839, 1995.
20. Pons, T.P., Garraghty, P.E., Ommaya, A.K., Kaas, J.H., Taub, E., & Mishkin, M., “Massive cortical reorganization after sensory deafferentation in adult macaques”. *Science*, 252, pp. 1857-1860, 1991.
21. Johnson, K.O., & Hsiao, S.S., “Neural mechanisms of tactual form and texture perception”. *Annual Review of Neuroscience*, 15, pp. 227-250, 1992.
22. Johnson, K.O., & Lamb, G.D., “Neural mechanisms of spatial tactile discrimination: neural patterns evoked by Braille-like dot patterns in the monkey”. *Journal of Physiology*, 310, pp. 117-144, 1981.
23. Robert J. Sinclair, and Harold Burton., “Neuronal Activity in the Primary Somatosensory Cortex in Monkeys (*Macaca mulatta*) During Active Touch of Textured Surface Gratings: Responses to Groove Width, Applied Force, and Velocity of Motion”. *Journal of Neurophysiology*, Vol. 66, No. 1, 1991.
24. Heller, M. A., “Improving the tactile digit span”. *Bulletin of the Psychonomic Society*, 25, pp. 257–258, 1987.
25. Paul Mahrer and Christopher Miles Mahrer, P., & Miles, C., “Recognition memory for tactile sequences”. *Memory*, 10, pp. 7–20, 2002.
26. Introduction to Sensation/Perception, Donald McBurney, Virginia Collings, pp. 69-95, 1977.
27. Fundamentals of Cognition, Mark H. Ashcraft. pp. 29-42, and pp. 100-129, 1998.
28. Donna M. Lloyd, Stanley J. Bolanowski, Louise Howard and Francis McGlone, “Mechanisms of attention in touch”. *Somatosensory and Motor Research*; 16(1): pp. 3-10, 1999.
29. Watkins, M.J. & Watkins, O.C., “A tactile suffix effect”. *Memory & Cognition*, 2, pp. 176-180, 1974.
30. Gilson, E. Q., & Baddeley, A. D., “Tactile short-term memory”. *Quarterly Journal of Experimental Psychology*, 21, pp. 180–184, 1969.
31. Heller, M. A., & Myers, D. S., “Active and passive tactual recognition of form”. *The Journal of General Psychology*, 108, pp. 225–229, 1983.
32. Christopher Miles and Hugh Borthwick, “Tactile Short-term Memory Revisited”. *Memory*, 4(6), pp. 655-668, 1996.

33. Bolanowski, S. J., Gescheider, G. A., Verrillo, R. T., & Checkosky, C. M., "Four channels mediate the mechanical aspects of touch". *Journal of the Acoustical Society of America*, 84, pp. 1680–1694, 1988.
34. Soto-Faraco, S., Spence, C., Fairbank, K., Kingstone, A., Hillstrom, A. P., Shapiro, K., "A crossmodal attentional blink between vision and touch". *Psychonomic Bulletin & Review*, 9, pp. 731–738, 2002.