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# Survey of Studies on Tactile Senses

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## Abstract

This survey is meant to serve computer scientists, mathematicians and others who need to get quickly acquainted with the most relevant results in the biology and psychology of the tactile senses but have little or no prior exposure to the field.

The survey is written from the point of view of a computer scientists studying artificial neural networks (ANNs). Questions of relevancy – what to include and what to exclude in the survey – are always very subjective. This survey tries to include biological and psychological knowledge and results that could provide ANN research with new ideas and insights. Also, the survey includes matters that could make the opposite to take place: ANN research providing biology and psychology with new ideas or insights.

Keywords: Tactile senses, artificial neural networks, literature survey

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# 1. OVERVIEW OF THE TACTILE SYSTEM

This section gives an overview of the structure of the touch sensory system in man.

The overview is divided in three parts:

1. Touch receptors. These are the "input devices" of the system. This is also where the various sensed physical quantities such as pressure or temperature are given a common representation[3].
2. Connections to brain. These are the "wiring" between the brain. This is also where a lot of preprocessing takes place.
3. Touch system in brain. This is where the information is processed into its final form. In this paper, the output or the final form is considered to be the output of the neurons that reside in various touch related "maps" in the brain and some neurons that are connected to the motor system directly. Any neurons that use this output are considered to be part of other systems.

## 1.1. Touch receptors

The main sensory receptors of skin are listed for example in [25]. The receptor types can be grouped in several alternative ways according to their properties. One main property is the type of the neural fiber to which the neuron is connected.

Receptors connected to *A-beta fibers* are:

1. *Pacinian corpuscles*, which are sensitive to pressure and vibration of 200-300 Hz and elicit the sensation of touch or vibration. These receptors are very fast in adapting to the stimulus. They are found both in hairless and hairy skin.
2. *Meissner's corpuscles* in hairless skin and *hair follicle endings* in hairy skin are sensitive to light touch and vibration of 30-40 Hz and they elicit the sensation of touch or flutter. Their adaptation to the stimulus is fast.
3. Merkel's discs (Ruffini endings) in hairless skin and Merkel's cells and Pincus domes (Ruffini organs) in hairy skin are sensitive to touch and pressure and they elicit the sensation of touch or pressure. They all adapt slowly to the stimulus.

Receptors connected to *A-delta fibers* or *C-fibers* are f*ree nerve endings*. They are found both in hairless and hairy skin and they adapt very slowly to the stimulus. They elicit the sensation of pain, temperature or mechanoreception. The ones connected to A-delta fibers are sensitive to cooling

[3]The system does have other sources of input, such as data from the other senses, but this is the main source.

and pricking pain, while the ones connected to C-fibers are sensitive to warming, burning pain and itch caused by chemical a stimulus.*

The sensitivities listed above are the *preferential sensitivities* of each receptor type. In addition to the preferential sensitivity, the receptors may be sensitive to other types of stimuli in a lesser degree.

A concept quite separate of sensitivity, yet related to it, is the *sensory modality*. The term refers to the sensation elicited by the stimulation of the receptor. For each individual receptor, the sensation is always the same regardless of the type of the stimulus or stimuli. For instance, if the nerves of hearing are stimulated by electricity instead of sound, they still elicit the sensation of sound. Some receptors elicit only one type of sensation while others, which are called *polymodal receptors* elicit several modalities.

The function of a sensory receptor – regardless of its type – is to transform the stimulus into a signal that can be processed further by the other parts of the nervous system. The first step of this transformation is to cause a change in the electric conductance of the *channel protein* and, thus, the conductance of the *membrane channel* of the receptor.

The process responsible for the change is called the *chain of transduction* and it is different in different types of receptors. However, it always leads to the change in conductance. For instance, in photoreception the chain of transduction leads from photon via rhodopsin, transducin, phospodiesterase and cGMP to the channel protein while in mechanoreception the chain is much sorter so that the movement, or the stimuli, directly affects the channel protein.

The second step is to create an *impulse discharge*[4]: The change in the conductance of the membrane channel causes a change in the *membrane potential* or, by other names, *receptor potential* or *generator potential*. This change propagates to the place where the impulse discharge takes place by the means of electrotonic potentials.

In some receptors the membrane potential and the impulse discharge occur in two different cells while in other receptors they occur in the one and same cell. Examples of both can be found, for instance, in [2] and [25].

Taking an engineering point of view, we can find at least three, mutually exclusive points which could be said to form the interface between the sensory receptor and the nervous system proper:

1. The point of impulse discharge. In this case, the electrotonic potentials causing the discharge would be in the domain of the receptory system and the impulses in the domain of the nervous system.
2. The membrane potential of the cell where the impulse discharge occurs. Note that the membrane potential may or may not be the same as the receptor potential.
3. The receptor potential.

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[4] The impulse discharge is the action of a nerve cell generating impulses, which are what we ANN people are used to think of as the output of a neuron

Any point prior to the receptor potential would make the interface unnecessarily complex, since we would have to have a different descriptions of the interface for different receptor types. The mapping between the receptor potential, the membrane potential and the impulses created at the point of discharge is very straight forward and could be accounted for by our current ANN models and thus any of these points could be used interchangeably. There may, however, be some cases, however, where our ANN models fail to capture some essential feature of the mapping[5]. In those cases, the point of impulse discharge would be the safest choice. One should not forget, however, that our ANN models may fail in this way in any part of the neural system, not just in the vicinity of the receptor system.

## 1.2. Connections to brain

The nerve fibers from the receptors lead to the spinal cord. These sensory fibers, also known as first-order neurons make connection to second-order neurons through synapses. The first-order neurons are physically divided into two groups which also correspond to two different functions. The bundle of neurons transmitting sensations of temperature and pain are called the spinothalamic system while the mechanoreceptors form the leminiscal system. The connections from first-order to second-order neurons vary between many-to-many and many-to-one synaptic connections. The second-order neurons interact with neurons either leading to the brain or down to glands and muscles, thus giving rise to some reflexes.

Two examples of such reflexes  are the simple reflex arch in the humans, or the "knee-jerk" reflex and the walking of a cat, which requires the control of the spinal cord only [6]

## 1.3. Touch system in brain

As the information from a single receptor arrives at the brain it has been combined with information from other receptors on its way through the first and second order units. All the ascending pathways from the spinal cord and the brain stem end at the *thalamus*.

The part of thalamus where the somatosensory pathways are connected is knows as the *ventral posterior nucleus*. This nucleus is further divided into lateral and medial part, the first being the entry point of the leminiscal and spinothalamic fibers and the latter that of the fibers from the *trigeminal nucleus*. The fibers from the trigeminal nucleus convey information from the facial area, which is therefore following different pathways than the information from the rest of the body.

[5]For instance, the mapping could include Fourier transformations.

Amongst the fibers terminating at the ventral posterior nucleus, there is a clear correspondence between the part of the body being stimulated and the fibers that are activated by the stimulus even though the information from an individual receptor cell has been mixed with the information from other receptor cells. Furthermore, the fibers are located so that they preserve the relations of the body parts.

The ventral posterior nucleus of the thalamus is connected to the *somatosensory cortex*, which is a part of the *cerebral cortex*. The connection relay cells preserve geometrical representation of the body found in the ventral posterior nucleus and project it onto the somatosensory cortex. The geometrical representation at the cortex is know as the “homunculus” and Homunculus was first studied by Penfield et al [22].

The body parts which have high acuity of perception, such as lips or fingers, comprise large areas of the “homunculus” and less acute parts comprise much smaller areas.

The homunculus is located in the *primary somatosensory cortes* or *S I*. Somatosensory information is, however, processed also in the *secondary somatosensory cortex* or *S II* [13]. The understanding of how these two areas are interconnected and how they interact has changed over the years. A quite complex picture has emerged. For instance, it was assumed that serial processing took place in the *association cortex,* while information was transferred from S I to S II. Later it was shown that this is not the case, see [20]. Instead, it turned out that several subparts of the thalamus pass somatosensory information on to one or more somatosensory areas. Furthermore, it was found that different areas within the somatosensory cortex process different submodalities. A more detailed discussion can be found, for instance in [20].

Another related geometrical concept is a *cortical column*. It was found that cortical units that fall on the same line tend to process information about the same submodality if the line is perpendicular to the surface of the cortex and different submodalities if the line is not perpendicular. See, for instance [23].

# 2. EXPERIMENTAL RESULTS

## 2.1. Temporal differences

Studies have been made to determine the limits of human perception of the temporal aspects of tactile stimuli and the results have been compared to other senses. Here are some of the results.

If two tactile stimuli are separated by about 5 ms or more, they are perceived as separate events. If the separation is less, they are perceived as one [7]. For hearing the threshold is about 0.01 ms and for vision it is about 25 ms[26].

The ability two perceive that two stimuli are sequential – as opposed to simultaneous -- does not necessarily give the ability to determine what the sequence, or order of the stimuli, is. Some experiments [11], suggest that the threshold for determining the order of two successive stimuli is about 20 ms for all the three senses: vision, hearing and touch.

Also, the ability to count the number of stimuli has been studied [16], and it seems that tactile sense is better for counting than vision but not as good as hearing.

## 2.2. Spatial differences

Similarly to what has been done with the temporal aspects of tactile stimuli, there has been many studies on the spatial aspects.

One of the most important measures used in those studies is the two-point limen (or threshold. The human subject is presented with either one ore two points of stimuli and is asked to tell which is the case. If the distance between the points of stimuli is less than the two-point limen, the subject perceives the two points as one. However, it has been shown , that practice can reduce the limen considerably [3].

Another widely used measure is the error of localization. In this measurement, there are always two stimuli that are separated by a small time interval. The subject is then asked to indicate whether the same point was touch at both times or not. The problem with this approach that it is not only ability to distinguish locations that is being measured, but also the ability to remember locations.

A good summary of the results of such measurements can be found in [26], for instance.

## 2.3. Sensitivity

Sensitivity to tactile stimulus or, in other words, the amount of stimulus needed in order to a person to sense it has also been studied [8, 14, and 15]. Thie threshold varies depending to (at least):

1. The location of the stimulus on the surface of the body [27]
2. The sex of the subject [31].
3. The frequency and temperature and the waveform of the stimulus[1], if vibratory.
4. The area of the contactor[6], the duration of the stimulus and the presence of surround [8]
5. The age of the subject [30]
6. The hormone levels of the subject [9].

[6]Contactor is basicly the source of stimulus and, thus, the area of the contactor is the area of the skin where the stimulus is present.

# 3. THEORIES AND MODELS

## 3.1. Gate control theory

Gate control theory was suggested by Melzack and Wall [18] in 1965 and a revised version [19] was published in 1988. The theory attempts to explain not only how pain is transmitted to the brain but also how can the same stimulus yield different magnitudes of pain sensation under different conditions. An example of the latter is when scratching, vibration, cold or warmth is used to reduce pain.

We start with the original version and work towards the revised version.

Figure **Error! Bookmark not defined.** shows the schematics of the original version of the theory: Both the large (L) and small (S) diameter fibers carry information from the receptors. This information then goes through the substantia gelanosa (SG) and the transmission (T) cell. Together SG, T and their connections comprise the gate control system, whose output is the output of the T cell.

In general, it is the S fibers that carry information about noxious stimuli and the role of the L fibers is to carry information about less intense mechanical stimuli. As the signal from the S fibers is routed through SG to T and onwards the double inhibition (indicated by the minus signs) actually strengthens the signal. The signal from the L fibers, however, is diminished in strength when routed through SG.

The following scenario gives a good insight how the gate control system operates:

1. There is no stimulus. The small activity of the small fibers tends to keep the gate somewhat open and the very small activity of the large fibers is not enough to close it.
2. A small stimulus is applied to the skin. Both types of fibers get more active. In relative terms, the activity of the large fibers increases more. This tends to close the gate and a smaller proportion of the barrage passes through.
3. The stimulus is strengthened. In relative terms, the activity of the small and the large fibers increase equally. Thus, the gate does not tend to close nor open further.
4. The stimulus is maintained for a period of time. The natural adaptation of the L cells makes them less active and the gate tends to open further.
5. The stimulus is still maintained but the L cells are kept active through, say, vibration. This tends to close the gate.

The original gate control theory also suggests that signals form the central control mechanism have effect on the gate control system. The details, however, are not explained.

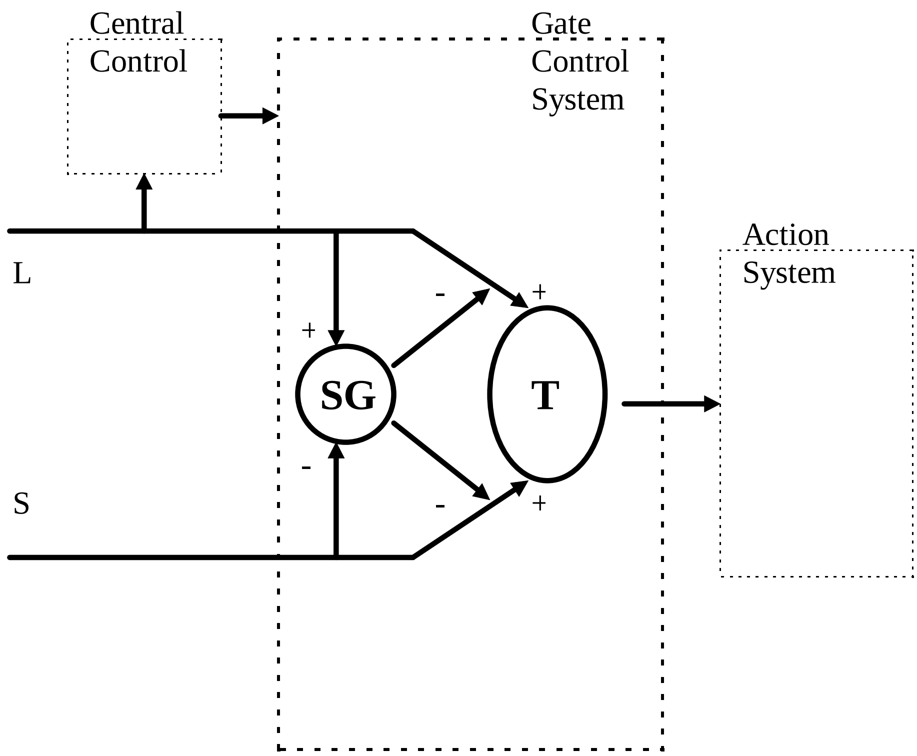


Figure 1. Original schematics for the gate control theory (From [18])(Scanned from [18])

The schematics for the revised theory [19] of 1988, are presented in figure **Error! Bookmark not defined.**.

The most notable change is that instead of just one type of SGs there now are two types distinguished by their connections and that the nature of some of the connections has changed. The way in which the central control mechanism affects the gate control system is now explained.

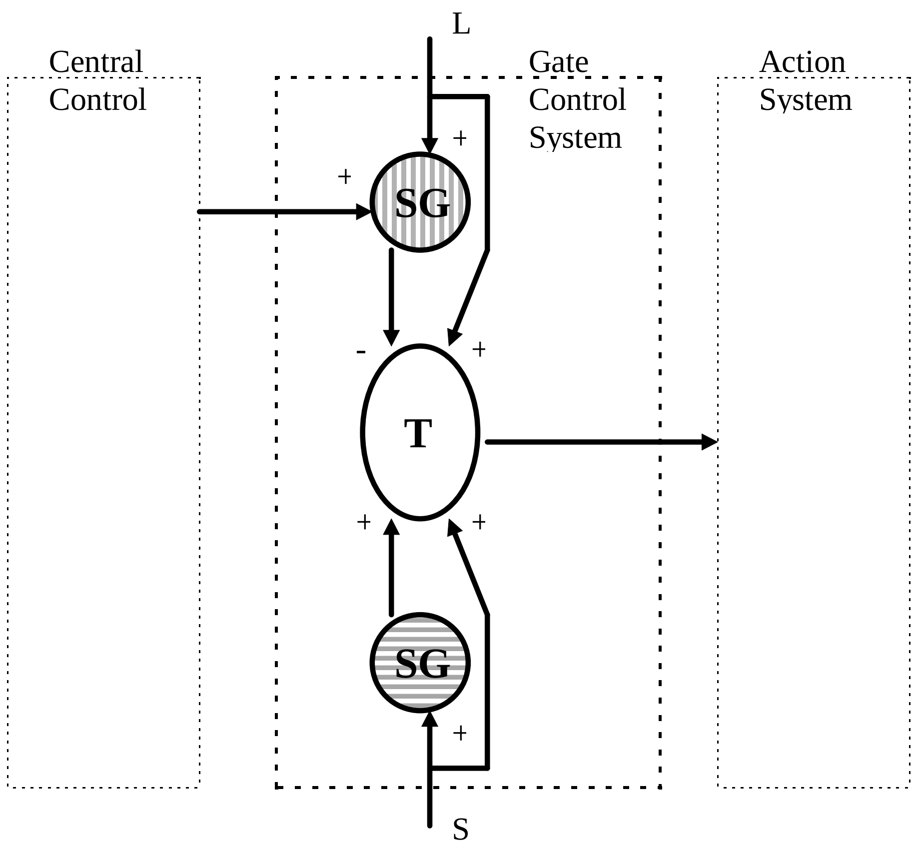


Figure 2. Revised schematics for the gate control theory

## 3.2. Power-law relationship

*Power-law* describes the relationship between the magnitude of the sensation and the magnitude of stimulus. It was first suggested by Stevens [28][29]. It is commonly given in one of the following alternative forms:

$$y = kx^{\beta}$$

or

$$\log(y) = \log(k) + \beta \log(x)$$

where y is the sensation magnitude, x is stimulus intensity and β is an exponent, which is specific to a modality. In reality, there is often an *absolute threshold* $x_0$, below which the stimulus does not evoke any sensation at all.

When dealing with values near the absolute threshold, the above equation are often altered so that $(x - x_0)$ or $\max((x - x_0),0)$ is used instead of x.

Some examples of the value of β, as given by Stevens, are 0.67 for the loudness of a 3000 Hz tone, 1.0 for the temperature of cold on arm, 0.5 for the temperature of warmth on arm, and 1.45 for the heaviness of lifted weights.

# 3.4. Double-filter model

Double-filter model [4] is a theory attempting to explain and to set bounds for the order in which tactile skills develop during infancy.

The starting point of the model is the realization that in order to get information about a particular tactile attribute may require certain motor skills. For instance, the perception of the temperature of an object requires very few and simple skills where as the perception of the configurational shape is a much more demanding task. Therefore, the age when the required motor skills are learned by an infant set a lower limit to the age at which the infant can exhibit the ability to perceive the tactile attribute in question.

Given this lower limit, the actual age when the infant exhibits the tactile skill is modulated by cognitive considerations. For instance, the perception of an infant under 8 months is mainly focused on the *aesthetic relevance* of the object – or, in other words, the pleasurable or interesting sensations achievable in the interaction with the object. Properties such as texture and compressibility have higher aesthetic relevance than for instance the weight of the object. At age of some 8 or 9 months the interest of an infant focuses on purposefully exploiting the object and weight becomes more important. This explains why the perception of texture and compressibility is developed at an earlier age than the perception of weight even though the necessary motor skills for the both develop at the same time.

Bushnell and Boudreau [4] suggest that the double-filter model is suitable for making predictions on the development of perception of tactile attributes. They suggest this approach to be applied to previously unstudied tactile attributes or circumstances such as blindness, but it could quite as easily to be applied to previously unstudied subject, such as artificial life forms or intelligence.

# 3.3. Intermodality

Most studies done on intermodality focus on touch and vision. In general, vision dominates over touch [10],[32], but not always. For instance, if the subject is given texture recognition tasks such dominance is not always observed [17] Also, if the subject is asked to estimate temporal rates, audition tends to dominate over vision [21].

Welch and Warren [33] concluded that visual dominance is more commonplace in cases where information is spatially distributed than in other cases. In the same paper they also proposed a general theory of intermodality relationships, which starts by acknowledging that in various kinds of situations the sensory modalities vary in their precision and, thus appropriateness to the task at hand. This appropriateness is then the determining factor in how the observer distributes his or her attention among the available sources of information: The observer tends to rely on the modality that is more appropriate.

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