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A low-cost electrocutaneous stimulator

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Abstract

The function of a man-machine interface is to translate between the two systems. In order to design better interfaces, characteristics of both systems have to be considered. The human brain is capable of learning new ways to interpret data, presented to it through any sensory modality. This property should be explored and used for new types of interface. Transcutaneous stimulation is a non-invasive way to examine the adaptive possibilities of the human sensory system experimentally, but such experimentation requires a transcutaneous stimulator. Because such stimulators are not commercially available, it is necessary to design and build one. In this thesis, the focus is on the exploration of new means of information transfer from a machine to a human user, taking full advantage of the plasticity of the human brain. This document can be divided in two parts: the first part introduces the theoretical concepts of brain plasticity and transcutaneous information transfer, the second part describes the design, building, and testing of a low-cost, low-voltage modular electrocutaneous stimulator.

1 Introduction: the importance of the interface - ubiquitous electronics

"Ubiquitous computing is the vision of a world in which computing power and digital communications are extremely inexpensive commodities, so cheap that they are embedded in all the everyday objects that surround us." - F. Stajano[1].

"Computing will be everywhere: in the walls, in the furniture, in our clothing, and in our bodies and brains." - R. Kurzweil[2].

Complex electronic devices have become ubiquitous over the past few decades. Bulky machines that started out as code-breaking devices have evolved into powerful computers present everywhere throughout modern life: from desktop work stations, to embedded controllers in home appliances, to pocket sized wearable electronics.

Significant factors in designing end user equipment have shifted from limitations in cooling, memory and raw processing power, to limitations in battery life, wireless connectivity and physical dimensions. Currently, electronics are being integrated rapidly into daily life, leading to a very important consideration: the end user does not need to, or want to, know about the inner workings of any (new) device, it merely interacts with, or through, it. Inevitably, one of the most impart factors in designing such a product becomes the user interface.

In the case of a (traditional) interface between a human and a machine, the design is generally limited by the bandwidth of (or spectrum covered by) human senses, or the latency of human response, rather than by the capabilities (latency, bandwidth and the like) of interfacing electronics. A notable difference in communications between humans and electronics (machines) is that humans communicate very slowly, and their communications are also error-prone and inefficient in comparison to machine-machines communications.

The interface limits all possible interactions between humans and electronics, and some hypothetical interactions are not possible with any of the (common) interfaces currently available. When interfaces for new devices are designed, information is transformed to fit through information channels provided by existing interfaces (like visual displays and touch input). However, some information can not be presented optimally through such displays. As long as only existing means of information transfer are considered during the design of new types of electronics and devices, the improvement of user interaction, on a fundamental level, can not keep up with the potential provided by technological progress in other fields.

A number of applications that could benefit from using a cutaneous display as part of an interface do not exist as of this writing, because such displays are too uncommon: no electrocutaneous displays are commercially available, except for a few (very expensive) medical devices. Therefore, the exploration of the possibilities of new types of interfaces relying on transcutaneous stimulation is practically out of reach of potential new researchers in the field, and hobbyists.

The possible applications of such displays are not limited to the displaying of trivial information, or even to the replacement of lost senses (such as vision), but instead, entirely new types of interaction could be imagined.

1.1 Document structure

Because all information from a machine is transferred to a human user through sensory modalities, it is important to understand the characteristics of the human sensory system before attempting to design a new way to transfer information into the human. Section 2 covers theory on the transfer of information between users and machines. A detailed background on the human sensory system is presented in section 3. In section 4, a non-exhaustive overview of the state of the art regarding cutaneous displays is presented, as well as descriptions of the physiology of the skin, and how to trigger receptors in the skin useful to the communication of information. Section 5 lists a number of possible reasons transcutaneous interfaces have not yet become commercially available. In section 6, it is concluded that the possibilities of the human input system could be explored more effectively if more researchers would have access to transcutaneous stimulators. The current unavailability of such devices gives rise to a need for a new stimulator design, meant to be built from commonly available and relatively cheap parts. The subsections of section 6 focus on the definition of design criteria for a modular stimulator for electrocutaneous stimulation. The aspects of electrode design and safety considerations are discussed in sections 7 and 8 respectively. The designs for the stimulator modules are presented in section 9. The performance of the modules is evaluated in section 10. In section 11, the best modules from section 10 are assembled into the first version of the stimulator, and the protocols for testing the stimulator are defined. The first prototype is tested on the author to determine if it is able to cause a perceptible stimulus, in section 12. Following the proof-of-concept experiments described in sections 11 and 12, a number of improvements to the prototype are presented in section 13. The improved prototype was tested as described in section 13, and its performance was evaluated in detail in sections 14 and 15. Suggestions for future experiments that fall beyond the scope of this thesis are presented in section 16. Additional photos and schematics are included in the appendix.

2 Transformation of information: the function of the interface

The function of an interface is to exchange information between systems, transforming information in order to make it compatible with in- and output characteristics on either side.
A user interface is used to communicate input to a machine (from a user), and output from the machine (to the user), therefore, the interface determines the range of possible interactions a user can have with a device.

As technology progresses, traditional user interfaces like the PC keyboard and game pads, are gradually being supplemented, or replaced by alternative interfaces, (most of the time) better suited to the task. With the introduction of smart phones, touchscreens became common on the devices because the old mobile phone keypads are inadequate to control some of the new functionality. Though desktop machines use a traditional physical keyboard to control similar applications, fitting a miniaturized (resulting in a less effective) version of the keyboard turned out to waste too much precious space to fit the screen whilst keeping the device pocket-sized. A solution suited to the problem, currently embraced by most manufacturers, is context-sensitive input through the touch screen: input coordinates are interpreted to match the graphics drawn on the screen at the corresponding location (for instance, icons on the screen or a virtual keyboard).

Specialized machines are created for solving many different problems, and for a significant portion of those problems, user interaction is required. The following example uses buttons, but the principle applies to all interface types. Some devices, like a remote control for a television set, are built to carry out a relatively small number of tasks, thus requiring a simple, optimized interface, while others, like a desktop PC, are meant to be versatile, and the interface can not be optimized for one specific task, without sacrificing the flexibility required for performing another task. Though the remote is a very simple device, it might have buttons the users would rarely use, like menu buttons or buttons to control features that are only available on a different (more expensive) version of the TV. Users unfamiliar with this specific remote might struggle to find the functionality they are looking for, but by trial and error, the user will probably find the correct button within minutes. However, the more complex PC keyboard often has context-sensitive button combinations, that are not consistent across programs or versions. Because the number of possible combinations and possible outcomes, many users will not use the "faster" keyboard shortcuts. Instead they would access the functionality through icons or menus (with either the mouse or keyboards), or they would ignore the functionality altogether. Experienced users would be able to control such programs more efficiently and effectively.

The quality of the integration of reality, as humans commonly accept it, and a virtual substitute could be covered by the term "immersion". Applications like games, telepresence, virtual reality, and augmented reality, are all about immersion: they aim to get the user to experience a virtual world from the point of view of a virtual entity, interacting with that virtual world through its interface. Common examples of applications designed to provide maximal immersion include modern fighter plane pilots controlling their machines through neural interfaces and surgeons operating through robotic surgery, where the surgeon interacts through a remote machine controlling a robot actually performing the surgery on a different scale. A more familiar example might be the flight simulators for training purposes. They are built to physically resemble a plane to provide the user with an experience as close to reality as possible. Various gaming devices have also attempted to provide a user interface alternative to the joystick or game pad, aiming to provide the user with better gaming experience, with varying success: from gun-shaped controllers, to chairs that provide feedback to the user in the form of sound and vibrations, to motion sensing through cameras like the Sony EyeToy (or later the Microsoft Kinect) or controllers that sense acceleration and orientation, like the Nintendo Wii.

The grail of immersion could be described as a virtual reality experience where a user could interact seamlessly with a virtual world providing a similar experience to the "real" world, but as of today, no interface exists that could mimic input to all human senses at once. Recently, the Oculus Rift virtual reality display has received notable media attention. What is special about this specific display to make it more suitable as a display for virtual reality in comparison to previous designs, is said to be the improved responsiveness to movements of the head. Note that successful immersion depends very much on input through multiple senses at once, being in sync! Section 3 elaborates on the importance and mechanisms of sensory integration and sensory interpretation.

2.1 Models of man-machine interaction

Models are meant to aid in the understanding of phenomena. The model of interaction between man and machine said to be the most influential in the field of Human-Computer Interaction (HCI), is Norman's 7-stages model of interaction[3].

The model describes an execution-evaluation cycle of seven (sequential) stages to approximate the interaction with a device, initiated by a user for a defined purpose. The 7 stages of Norman's model of interaction[3]:

1) The user defines a goal
2) The user forms an intention
3) The user specifies a sequence of actions (as input through the man-machine interface)
4) Actions are executed (by the device)
5) The user perceives the new state of the system (as output through the man-machine)
6) The user interprets the state of the system
7) The user evaluates the outcome

The model can be divided in "setting the goal", stages of execution (stages 2-4), and stages of evaluation (stages 5-7). When users encounter problems with interfaces, this is often due to the difference between the user's expectations, and the systems abilities: Norman describes the distance between the actions formulated by the user to reach a goal, and the ability of the device to be able to execute those actions as expected, as the "gulf of execution". The "gulf of evaluation" refers to the effort required by the user to perceive and interpret the results of the execution phase. A small "gulf of evaluation" means the outcome is presented by the device in such a way that the user is able to perceive, interpret and evaluate the result with little effort[3].

It is noted that Norman's model only considers the interface from the view of the user, an extension to the model was proposed by Abowd and Beale[3]. The model by Abowd and Beale consists of interaction between four components: the "user", the "system", the "input" and the "output". A graphical representation of the interaction framework is shown in figure 2.1. The user and system (device) are said to understand different languages: The system (device) communicates to the interface in "core language", the user communicates to the interface in "task language". The interface translates between the user and the system. The only way the user can tell the system what to do is by specifying intentions through the "input" component of the interface ("articulated" in the "task language" understood by the interface), and the only way the user perceives the state of the system is through the "output" component of the system[3]. The translations between components in the cycle are shown as gray text in figure 2.1.

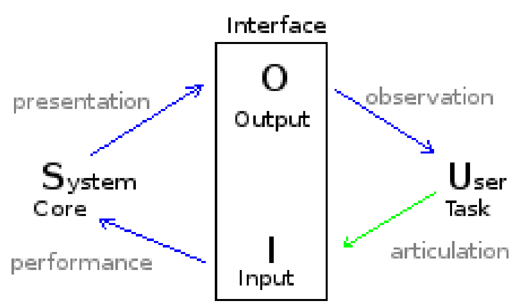


Figure 2.1: Abowd and Beale interaction framework. Translations between components shown in gray. Adapted from Dix, Finlay, Abowd and Beale[3]. Green indicates user control, blue indicates software control.

Although the Abowd and Beale model of interaction allows for more consideration of the machine side of the interface in comparison to Norman's model, the explanation of this model in the book Human-Computer Interaction by Dix, Finlay, Abowd and Beale[3] still assumes all cycles are initiated by the user (the green "articulation" arrow in figure 2.1): the user specifies a task through the interface because of a goal the user has defined. The system merely executes the users commands and presents its new state to the user for evaluation. This model is not suitable for all types of interactions between users and machines. Devices can take the initiative instead of the user. It is easy to image an interactive game wherein the user responds to problems presented in the game. The user is still specifying personal goals, but those goals are specified in reaction to an observation of the machine state, which was initiated by the machine (not the user!). Another example would be a ringing phone. The machine initiates the ringing, the user responds to it. Instead of assuming the system output is always a response to an action initiated by a user, it is more realistic to consider both possibilities: in some cases, the cycle is initiated by a user, in other cases, the output of the system will be the first step in the cycle.

2.2 Interface design

Design is about reaching a goal, under constraints imposed by the relevant components and situation.

To understand the possibilities and impossibilities of interfaces between users and devices, a number of factors needs to be considered:

1) The type of information that is to be communicated (in either direction)
2) The minimum speeds of information transfer (and latency)
3) The properties (and limitations) of input and output devices (for both sides)
4) Encoding information for transfer
5) The translation of information, (considering limitations of respective input and output devices)
6) Reducing interference with normal operations
7) The robustness of the information transfer

The very first thing to determine when designing an interface, is the goal of the interaction: what information is meant to be communicated, while also taking the minimal speed and latency required for functional operation into account. The second step is to define and work around constraints: determining the best way to encode the information in such a way that the transfer of information can be understood, and appropriately translated, by the appropriate input or output on either side. Other considerations include the reduction of errors during transfer or translation (and interpretation) and the impact the data transfer has on normal operations: for instance, consider an auditory display that produces a continuous series of loud bleeps. The bleeps would introduce too much noise (and thus override or impede other important input) to use the ear for receiving normal input.

To evaluate the performance of a new man-machine interface (from the point of view of the end user), a number of factors (relating to usability in practice) are important: learning curve (is it easy for the user to learn how to use the interface?), intuitiveness (does using the device feel 'natural' to the user?), and usefulness (is the user able to use the device as intended through this interface?). For instance: the desktop PC is commonly used as a typewriter, so it is only natural to find an interface similar to the one on a typewriter: a keyboard to enter characters (input) and a display for feedback and context (output). As the interfaces of desktop computers changed to graphical environments, interaction through a mouse became common. The mouse allowed for an additional dimension of interactions, opening many new possibilities, like selecting and dragging objects across a desktop or program space displayed on a screen, (3D)drawing programs and games. For instance, real-time strategy games are relatively hard to control without the common PC interface: a combination of a keyboard and a mouse for input, with a screen and speakers for output.

2.3 The informational value of a bit

In order to transform information into a form suitable for transfer, an encoding scheme is needed. To design an encoding scheme, crucial parameters are the information content (resolution of the range of possibilities) to be communicated, and requirements of the information rate.

Information rate defines the number of bits needed per second to describe the number of symbols per second, multiplied by the informational content of a symbol: rate(bits/sec) = (decisions/sec) * log2(number of choices in decision). However, an exact quantification of information is sometimes hard to give, especially when it comes to information that is interpreted from sensory input. Kaczmarek uses a clear example to illustrate this point[4][5]: Consider a visual recognition task where a human is asked to categorize photos of 10 human faces as either male or female. Assume the task could reasonably be completed in 10 seconds. The subjects response rate becomes: (1 decision/sec) * log2(1) = 1 bit/s. It is obvious that the actual rate of visual information input from the photo is larger. The reason for this difficulty in the quantification of information rate, is that the decision "male" or "female" as entered in the formula, is seen as a single decision. However, this is a classification problem that the human brain is trained exceptionally well to solve. A lot of subconscious information processing happens in the brain to get a "male" or "female" classification result, the task of face recognition depends on complex visual input. The minimal visual input required to solve this problem results in an information rate much larger than 1 bit/s. Three important conclusions can be deducted from this example:

0) The quantification of information is hard, especially when it comes to human input, processing, and output.
1) The information rate of the output is not a reliable indication of the input information rate required to reach that output.
2) Human pattern recognition is both powerful and taken for granted, as the human is often not even aware of the complexity of its subconscious processing capabilities.

An important characteristic of information is its complexity: the minimal data required to describe the meaningful (non-random, unpredictable) content of the message, in such a way that it can not be compressed any further in a lossless way.

From a computer-to-human point of view: to present information to be communicated via any type of display in an efficient way, redundancy of data should be minimized in the design phase of the scheme to translate (encode) data. From a human-receives-input point of view: processing complex patterns of (input) data becomes easier with practice, as paths in the brain form and strengthen (learning). Learning pattern recognition for a radically new type of data encoding is similar to learning to read. When designing a display relying on a new way to interpret data, a user would require a lot of training before the device could be considered to be functional for that user. Such a learning curve is currently not considered to be acceptable for commercial products, so common displays are (primarily) limited to combinations of existing (commonly recognized) patterns for the encoding of data. The learning curve is a very important reason displays that rely on radically different symbols (patterns) to transfer data do not commonly exist. For instance, this learning curve is likely the main reason most humans can not read bar codes fluently in practice.

Though exact quantification of information rates of sensory inputs is hard, the order of magnitude of information rate for data interpreted from sensory input can be approximated. A practical way to compare effective information transfer rates, is to find a way to compare the measure words/second to bits/second. Shannon estimates the information content of a single written letter as part of an English word as 1 bit, the average word containing 6 letters[6]. To convert word rate (words/minute) to information rate, 6(bits/word)*wordcount/60(sec/min) gives 1 word/min is equal to 0.1 bit/sec[7]. Schmidt[8] estimated the informational bandwidth of (understanding) speech is about 40 bits/s, while the informational bandwidth of reading text is close to 30 bits/s. Average braille reading rates of 50-200 words have been recorded for trained subjects[4][7], corresponding to a bitrate of 5-20 bits/second. Bach-y-Rita states the following: *"Thus far, however, the highest rate of information transfer actually used by a nerve fiber in a living organism has not been determined."*[9].

3 Human I/O

All signals entering the brain from sensory neurons (afferents) are physiologically equal, only the processing and interpretation of those signals in the brain gives meaning to a stimulus. The brain is processing input from all senses in a fashion similar to the way electronics receive information through inputs: all streams of digital information (input) are as equal as all streams of sensory input are. Their real meaning is only derived from context.

Bach-y-Rita illustrates this principle[10][9]: *"We do not SEE with our eyes; the visual image does not go beyond the retina, where it is turned into patterns of pulses along nerves".*

Humans perceive the world as an integrated interpretation of the input provided by their senses of touch (vibration, pressure, temperature, pain, itch, wetness), movement and orientation (vestibular), smell, taste, hearing, and vision, but the meaning of every input is implied by their connections to other neurons, and a context made of parallel input and previous experience.

Because the human perception of the world is fundamentally limited to sensory input, and therefore, limited only to perceive phenomena within the range perceivable through the senses, the world as a human experiences it is a direct result of the configuration of the brain. Not only does reality include many phenomena outside the scope of human perception, the idea has been considered that reality as humans accept it, is not real at all.

Rene Descartes questioned the reliability of the human senses to provide an accurate description of reality. He writes in Discours de la Méthode[11] that because all information about the world is gathered through human senses (and there is no way to verify the reliability of those senses), the mental projection of the world might be an illusion, not anymore true than a dream. As he continues to think about his doubts about the true existence of the world, including his own, he reaches the conclusion that he must exist because otherwise, he would not be able to think about his own existence in the first place, with the world-famous quote "I think, therefore I am".

As we have to rely blindly on our senses to tell us what is real and what is not, obvious potential exists for the creation of applications that rely on advanced (targeting multiple sensory modalities) forms of virtual reality. The concept of virtual reality is about supplying the human senses with crafted input, in order to fool the human brain to accept the crafted reality as actual reality. In the 1999 movie The Matrix[12], this concept is illustrated: In a distopian future, humans are unaware that the reality they are living in is in fact a virtual world called the matrix, crafted by intelligent machines. Because all sensory input is provided on a neural level, humans have no reason to suspect their reality is actually a crafted hallucination, while their bodies, in actual reality, are being used as power sources for said intelligent machines. The point is made that it does not matter to any human individual whether reality is "real" or not, as long as reality is accepted as being real by that individual, beyond any doubt. The movie emphasized this principle in a scene with the quote "ignorance is bliss".

3.1 Brain mechanisms

An environmental stimulus is picked up by the relevant sensory receptor, from where the stimulus is encoded into a train of pulses, as input to the central nervous system. The stimulus becomes part of a greater set of inputs, pattern recognition after spatial and temporal integration of stimuli (and internal context) leads to the mental representation of a concept (percept).

The origin of sensory input (such as the eyes, for visual input) determines the location of the mental projection in a three dimensional space, rather than the actual location of the nerve inputs. This phenomenon is called distal attribution[13][14]. Consider a situation in which a human operator controls a remote robot. If sufficient sensory information of the robot is presented to the human operator (for instance, via visual and auditory displays), and if a feedback loop exists (the input from the senses change according to movement of the operator without a significant delay), the operator may experience the feeling of "being" in the location of the robot instead of his real location. This principle is called telepresence[4][13].

Sensory systems are robust and fault-tolerant, they have to be to be able to adapt to a wide range of possible inputs. A number of studies have examined the effects on sensory interpretation of visual input after distortion of the image by means of special lenses that distort, flip, tilt or displace.[15]. One fact that can be concluded from all those studies, is that the brain will adapt (within its limitations), to cope with the new input (and transform the new input, in order to interpret it the same way as regular input) in a process called perceptual recalibration[15]. Over the past decades, it has become common knowledge that it is possible to present (and learn to interpret) new types of information through a sensory modality, including data regularly received through other senses[9][15][16][17][18].

This principle and its uses will be explored further in the sections brain plasticity and sensory substitution (sections 3.5 and 3.6 respectively).

3.2 Neural communications

In order to design interfaces meant for communication with a human brain, it is important to understand on a basic level how the brain receives and processes signals - strengths and weaknesses of the system as a whole, are a consequence of its layout, as well as the workings of communications on the neuron level.

The nervous system is made up from neurons forming the central nervous system (the CNS is composed of the brain and the spinal cord, estimated at 10^{11} neurons[19]) and the peripheral nervous system (nerves outside the CNS)[20]. Generally, processing happens in the CNS, while the peripheral neural system provides input and output channels.

Neurons are cells that use electrical and chemical (neurotransmitter) signaling to process and communicate data. Figure 3.1 illustrates the basic structures of a neuron. A neuron commonly has multiple inputs (dendrites) connected to its cell body, and one axon that carries an action potential (output). To illustrate the order of magnitude of the number connections a neuron has to other neurons: neocortical neurons are connected on average to 7000 other neurons[21].

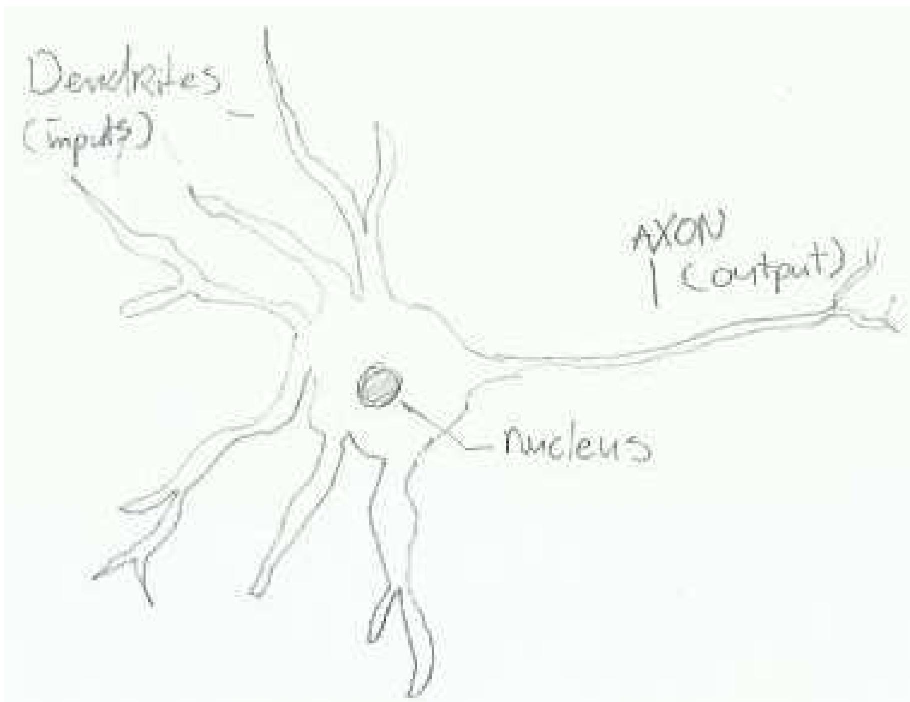


Figure 3.1: Drawing of important structures of a neuron.

Electrical signals are used to propagate a signal within the limits of the membrane of a single neuron, neurotransmitters (small chemicals) are used to communicate an action potential at the interface between two neurons (synapse). A synapse is the communication surface between a cells axon (output) and another cells dendrite (input). The input signals at the dendrites can be interpreted either as positive or negative stimuli of various magnitude, and once the total summed input value reaches a threshold, the neuron generates an action potential (it fires). The general shape of an action potential is shown in figure 3.2. In rest, the neuron has a negative potential over its membrane (the actual value varies, but -70mV is a common resting potential), maintained by the trans-membrane protein Na+/K+ ATP-ase. This protein pumps 3 Na+ ions out of the cell, while pumping in 2 K+ ions, netting a negative charge. The cell builds up pressure in the forms of a gradient of K+ (high concentration inside a neuron, lower concentration outside), a gradient of Na+ (lower concentration inside the cell than outside), and the voltage potential across the membrane. Under these circumstances, all Na+ gates are closed (and the membrane itself is not permeable to Na+ ions), but the membrane is leaking K+ ions (relieving pressure) to reach an equilibrium state where all contributing factors are balanced. To produce an action potential, the potential across the cell membrane is reduced gradually (it gets less negative), until the moment the threshold is reached, causing an all-or nothing action potential to migrate over the membrane. The voltage-gated Na+ channels (their state depends on potential over membrane) open, resulting in a positive feedback loop that causes a depolarization wave to propagate across the cell membrane, as more Na+ channels open, and Na+ ions rush in, because of pressure caused by both the voltage and the Na+ gradient. With a short delay, gates open to allow K+ ions to flow freely out of the cell. The potential across the membrane falls below the resting potential. The moment immediately after the action potential (absolute refractory period (commonly about 1 ms), the neuron can not fire again because the gradients have to be restored first. A moment after that (relative refractory period, commonly 2-4 ms), the cell can fire again, but it needs stronger stimuli. After the relative refractory period, the cell is reset to normal operation: the resting potential is restored.

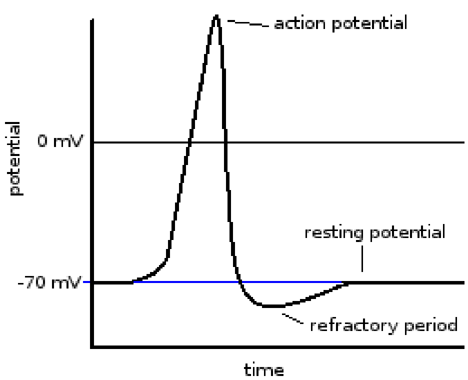


Figure 3.2: The neural action potential.

Once the action potential reaches a synapse at the end of the axon, neurotransmitters are released (from the pre-synaptic terminal), and the chemical signals are treated as input to the dendrites of the next neuron (on the post-synaptic terminal). Weights are assigned to all inputs received at a neurons synapses (an input can also have a negative weight value), and an implicated summation function determines if the neuron will produce an action potential in response to the input pattern[20].

In 1949, Hebb published a theory on the formation and strengthening of neural pathways (learning)[20]: if the axon of neuron A repeatedly takes part in the firing of a neuron B, some process takes place to increase the weight (and the other way around) on the input from axon A in the firing calculations of neuron B. A connection (synapse) between two neurons that becomes more effective because of synchronized firing of the two neurons involved is referred to as a Hebbian synapse (*"Neurons that fire together, wire together"*)[20][22].

The simple perceptron is modeled after these properties of neurons, it was designed to imitate, and take advantage of the processing capabilities of networks of biological neurons, with artificial neural networks implemented in software[23].

Neurons encode data in frequency modulation of action potentials (the delay between action potentials is varied). The principle of encoding sensory information in action potential frequency is shown schematically in figure 3.3. The letters a, b and c refer to a: a situation without input, b: a situation where input intensity is translated to firing frequency, and c: a situation where the neuron has reached its maximum firing frequency, so it can not fire faster in response to more intense stimuli. If a sensory neuron is not receiving neurons will still fire occasionally (functionally equivalent to a keepalive signal). A more intense (and longer) stimulus is encoded as a greater number of action potentials, this principle is the basis for spiking neural networks[24]. The encoding of the intensity of sensory information is not achieved in a linear fashion[25][26].

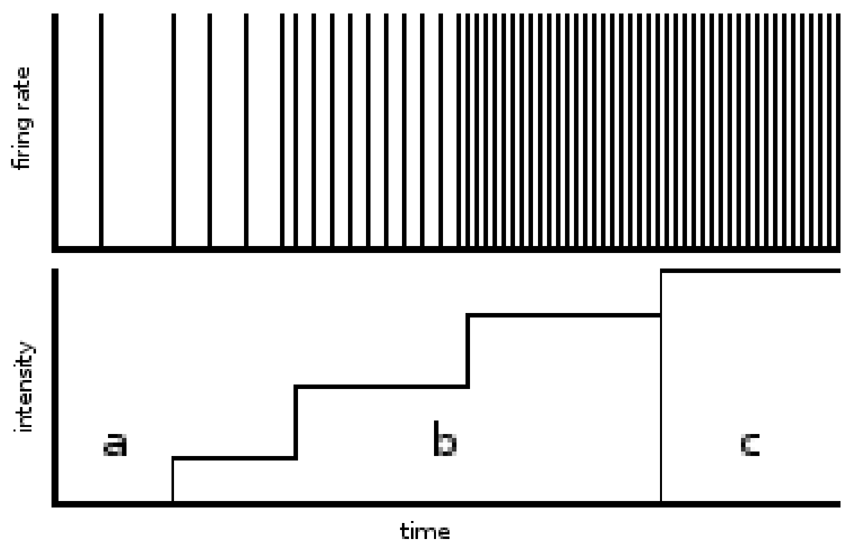


Figure 3.3: Neural input translation: stimulus intensity encoded in firing rate. phase a: no stimulus, b: stimulus encoded non-linearly to firing rate, c: maximum firing rate of neuron is reached.

In the initial stages of brain development, many more neurons are created than will survive in the end. Neurons extend their axons (guided by chemical gradients), and only those that successfully connect to other neurons stay alive, the unconnected neurons are pruned. If neurons become unused (for instance, when neurons no longer receive any input from other neurons because of brain damage) they also die. In some cases, neighboring axons may branch and connect to the open spots. As experience is gathered, new connections between neurons are formed (and old, unused paths might be "unmasked"), improving relevant brain performance[20][22].

Once a certain neural path has been strengthened, a neuron would be less likely to use its weaker connections in the future, and this would lead to a feedback loop where the strong connections could not be replaced by potentially better connections. This problem is solved by the fact that neurons sometimes produce "random" action potentials, that can initiate new paths (if the new paths turn out to be less useful than original paths, they will be used less, as expected), and they also keep neurons alive that are temporarily underused[20][22].

On a high level, all fine-grained neural input is provided to the CNS through afferent neurons, conveying sensory information, and fine-grained output is provided through efferent neurons, controlling muscles. The CNS also uses a less selective, global broadcasting system based on chemicals (like hormones) transported through the bloodstream: biologically active chemicals may alter the response of a neuron to a stimulus. Well-known examples include the effects on the nervous systems of caffeine, nicotine, ethanol and other drugs/poisons.

As noted previously, it is important to consider the physical properties of the human input and output system when designing a man-machine interface, since all information communicated through inputs and outputs to and from the human, is carried through neurons. Evidently, many specialized neurons exist, and properties like the resting potential, refractory period, and expected firing rate vary per neuron type, and situation and location. The maximum number of pulses per second a neuron could theoretically send (for input or output purposes), depends on the absolute refractory period of that neuron. Estimates based on the absolute refractory period are in the order of magnitude of 1000 pulses per second (from an absolute refractory period of 1 ms). Realistic numbers can be obtained by measuring firing rate of input and output neurons in humans. Data on firing rate of neurons controlling muscle contraction has been compiled and presented by C. De Luca in "Physiology and Mathematics of Myoelectric Signals" (1997)[27]. Firing rates of motor units increase with muscle force. Though the actual rates vary per muscle type, rates of 100 pulses/sec have been recorded in the short toe extensor muscles[27]. The bandwidth of sensory systems suitable for human input in a man-machine interface, is more complicated than recording single afferent firing rates, because input data is often presented in a parallel fashion. High-level bandwidth of sensory systems is discussed in the next section.

3.3 Bandwidth of the senses

Common displays rely on the visual or auditory senses to provide information (input) to humans. No technologies that could lead to displays based on smell or taste have been developed yet. Use of vibration is not uncommon in interfaces between humans and electronics, but the information communicated by means of such vibrations is extremely limited. Other receptors in the skin, (pain, heat, cold) are currently not being used as information channels for man-machine interfaces.

Ergo, the only three viable input channels to get information into the human available through current technology are sight, hearing and touch. Information presented through these channels is interpreted differently by the brain, and every input channels has its own characteristics. Sight and hearing are often used in displays, and the properties of both are said to be well-understood. The skin as input channel, however, has not yet been explored fully.

Input from the visual sense is based on pattern recognition over spatially- as well as temporally integrated information from an array of photoreceptors responding to photons (electromagnetic radiation with a wavelength between 350 and 700 nm[20]) in the eye. The bandwidth of the visual sense at the receptor level is estimated at 10^7 bits/s by Schmidt[8], and at 10^6 by Jacobson, with a rate of 5 bits/s per fiber[28]. Visual patterns are interpreted both as parallel (images) and serial (movement) patterns.

Auditory input is received as pressure waves in the 20 to 16000 Hz range[29], transmitted from the ear drum to the cochlea, where the mechanical signals are translated to neural signals. Auditory information is interpreted primarily as serial input patterns (such as sounds). The bit rate on the receptor level is estimated at 10^5 bits/s by Schmidt[8], and at 10^4 bits/s by Jacobson, with a rate of 0.5 bits/s per fiber[30].

The theoretical bandwidth, at the receptor level, of the skin is estimated at 10^6 bits/s by Schmidt based on counts of afferent (sensory neurons) fibers[8], but it's estimated at less than 10^2 by Kokjer, with a rate of 5 bits/s per fiber[7]. Szeto and Saunders[25] estimate the theoretical maximal bandwidth of a single stimulator electrode to be 1200 bits/s (4 bits of information encoded in intensity, presented at 300Hz). They also state that the number of independent, simultaneous signals (from an array of electrodes) a human subject could feasibly track is limited (less than 32, at least 3). The general agreement at that time was that the actual bandwidth of electrocutaneous communication is 2-5 bits/s per electrode. According to Szeto and Saunders, higher bandwidths would require multiple electrodes[25].

3.4 Brain plasticity

Sensory substitution is only possible because of brain plasticity[18], which allows the perceptual system to change in order to be able to process and interpret new types of input. Bach-y-Rita defines brain plasticity as "the adaptive capacities of the central nervous system - its ability to modify its own structural organization and functioning"[18]. Mere decades ago, the suggestion that plasticity could be an inherent property of the adult human brain was forcefully rejected by the mainstream neuroscience[22]. It has since been accepted that the human brain is not a static machine. The brain is capable of rearranging itself, in order to to gain the ability to interpret and process new types of neural signals. Types of input not previously offered to the brain through a certain sensory modality can be processed after a period of learning[9][15]. Therefore, the brain can interpret information from sensory substitution devices, even if the input data is not presented in the same shape or form, as the data would have been presented to the "regular" sensory modality[15], thus it is only necessary to encode information in such ways it can be communicated to the brain (through any sense), where it can be interpreted and put into context[10].

3.5 Sensory substitution

Sensory augmentation systems alter or improve the functioning of existing sensory modalities (like glasses, or a hearing aid), sensory substitution is about the use of a sense for receiving information usually received by another sense[16]. For the sense of touch, substitution may also be the use of one area of the skin to receive tactile information normally received on another location[17].

The most common and widely integrated sensory substitution system is said to be braille[18]. The blind can read words by feeling patterns of bumps with the fingertips, instead of the traditional sight-dependent way to read text. However, the author would indicate that sensory substitution systems are everywhere (some may be more common than braille), but that such systems are rarely recognized as being sensory substitution systems. For instance, many common displays are in fact sensory substitution systems in the sense that information usually received through other modalities is presented to the eyes or ears, like "loudness" displayed visually on a Volume Unit meter (usually, loudness is perceived using the ears instead of the eyes), or object proximity indicated aurally as an aid for parking a car (usually, proximity is estimated visually).

If a subject is using a sensory substitution device, and if there has been enough time for the brain to adapt to its input, the subject experiences the input as taking place at the point in space corresponding to the location of the "artificial" input device (regardless of its actual orientation and distance to the subject), rather than the site of stimulation interface (like the electrode location on the skin). An example of this is described by Bach-y-Rita et al.: After sufficient training, blind subjects receiving input from a camera through an electrotactile electrode array, no longer consciously perceive the stimulation at the electrode site. Instead, they interpret the data and perceive it directly in three-dimensional space[10].Though the tactile-vision substitutions described in literature provide limited resolution displays (100-1032 point arrays), visual processing still leads to effects like parallax, perspective, looming and zooming, and depth judgments[10], input from other senses is integrated into the percept. This principle works both across sensory systems, and within a sensory system (displacement of a stimulus)[4][18].

The visual processing of data from (for instance) a tactile display by a blind subject only works if that person was not born blind (meaning the subject has learned to process visual information the natural way). The blind subject has not lost his ability to see (to have a brain able to interpret visual signals, usually from the eyes), merely the ability to receive input through the eyes. As long as the rest of the pathways for visual processing are intact, alternative senses might be used to deliver data to the brain, and after a period of training, the new input should be interpreted as visual information[18]. This adaptation (described by Gonzales et al as "The late-learning perceptual process") is functionally a recalibration of the perceptual system[15]. Sensory substitution can only work because of an adaptation in the neural pathways (resulting in the "correct" and "efficient" processing of new information), and this adaptation is achieved through a learning process that takes time and feedback. Important factors to consider regarding the learning process to recalibrate sensory input are examined in section 3.7. The reason for the difference in theoretical and practical bandwidth is discussed in more detail in section 5.2.

3.6 Sensory overload

The brain needs to adapt to be able to cope with new types of input streams. Thus, when introducing a new type of display that uses the sense of touch as input device, subjects are likely to be limited by sensory overload. The brain has not formed enough connections yet to support processing of unusually large amounts or types of data, and extensive training is required to develop this ability. Szeto explicitly mentions the problems of limited training time and sensory overload[31]. He also states that there is a difference in tactile sensitivity between a blind person and a sighted person because the blind person uses the sense of touch extensively to navigate the world without vision. This difference leads to the fact that a blind person is able to process (and, in the context of the experiments, interpret) more data per second (up to 5 bits/s), while most sighted persons are probably overloaded at 2 bits/s[31].

3.7 Sensory substitution: learning and feedback loops

"You create your brain from the input you get." - Paula Tallal

As mentioned previously, the brain interprets signals from neural inputs through a context created both by "hardware" (location of physical neural connections) and "software" (input weights, learned pattern recognition). All signals sent by neurons that are assumed to be connected to sensory units are expected to deliver information that is to be interpreted, and integrated into a mental model of the world by the brain. Possibly the most important requirement for the correct integration (and interpretation) of sensory information is a feedback loop, because without it, the second most important requirement (learning: the training of pattern recognition abilities) becomes practically impossible. Learning is on a very low level the process of the creation, strengthening, or weakening of neural connections in reaction to experience: it attempts to find and classify correlations between patterns of input. As an action is initiated (by means of muscle control), the reaction can be observed (the window of visual information representing the world "moves" accordingly), and a mental model of the action/reaction correlation is constructed for the relevant patterns of input and output. Therefore, a feedback loop is crucial because it makes a trial-and-error method of correlating action and reaction possible.

The mental model of the world (everything you see, feel, hear, smell, etc) is "learned". The way information from sensory modalities is experienced is primarily a result of a life-long training process in which input data is categorized to make sure the model of the world stays as consistent as possible, even when input information varies: this feature makes the sensory system very robust. An obvious example why this robustness can be considered of vital importance: otherwise, a change in light color or intensity (which is incredibly common under natural conditions) might lead to a difference in object boundary determination or object classification, and visual orientation and depth-perception could not be reliable. To build this model of the world, the brain needs a feedback loop between input (from senses) and output (movement from muscle) to determine the location in three dimensional space for all receptors sending stimuli, effects like occlusion, parallax, zooming and the like are not necessary limited to the visual sense. This principle is illustrated by the following quote:

"In the normal course of human development, the perceptual systems are naturally calibrated through the feedback process of perceptual learning that a person will have undergone since infancy." - J.C. Gonzales et al. [15]

As man-machine interfaces, notably displays, require a way to get information into the human, the existing input channels are obvious choices, and adding new ways to receive new types of complex input through existing human interfaces is actually very common. In fact, learning to understand language, or learning to interpret characters and entire words in order to read is considered normal to the point where the brains ability to learn new modes of input is no longer seen as something special: it is just something the brain does. When it comes to the translation and interpretation of new types of patterns and signals, the human brain gets better at recognition and classification with increased experience. The most important conclusion is that the interpretation of input from senses is not fixed, it is possible to learn to interpret and use new types of input through existing neural connections.

Learning a new mode of input (the training of pattern recognition in the brain) requires time and a feedback loop[4][9][15]. These points can be illustrated by reports from the book *Brain mechanisms in sensory substitution*[9] by P. Bach-y-Rita: With voluntary movement, recognition is improved. If the subject controls a camera that transfers a very low resolution image to the brain through a cutaneous display, the perceived resolution is many times greater because the brain "scans" the environment by simply moving the sensor and integrate the information over time[9][18]: the feedback loop enables the brain to correlate input spatially as well as temporally in order to form the percept[4][9]. If the subject was not allowed to control the camera movement, performance decreased dramatically[32]. If the subject was to interpret data from a static display, the resulting level of performance was simply inadequate: *"we can not* *recognize patterns by static touch"*[9][33].

Processing of data in the CNS is effectively compressing patterns of sensory input data. Bach-y-Rita states that the CNS should be able to participate in all phases of processing[9]. Effectively, he warns that if data is presented in a "simplified" way through the skin (because of lossy compression methods that reduce the number of possible input patterns to be presented through a tactile display), the CNS can not use any information that was deemed unnecessary (by the designer of the code in an attempt to minimize the load on the skin receptors)[9].

Szeto and Saunders noticed the following during their experiments to compare the effectiveness of data encoding schemes: if subjects had time to train for 2 hours or more before the actual experiments, the subject-to-subject variance in learning was great enough to obscure the actual effectiveness of the codes to be compared[25]. Szeto and Lyman note that the easiest (fastest) code pair to learn was two low pulse rate modulation codes matched together[34]. Compare this to the time it would take to learn a language, or to learn to read a new character set.

In order to be able to compare waveforms and encoding schemes to display information through the skin (and identify the best method for data transfer), data presented should be of sufficient complexity, and the only way such data could be interpreted is after a sufficiently long training period, of adequate quality. Kaczmarek et al. compared training time to performance for the optacon tactile vision substitution system as a device to read[17]. The users could immediately recognize vertical, horizontal, and diagonal lines, and after 40 hours reading a speed of 10 words/minute was achieved. Further training increased the speed to 28 words/minute, the exceptional(sic) reading rate of 90 words/minute was reported to be possible after 100 hours of training. Some users can learn to recognize familiar object after 20 hours of training[17].

4 Cutaneous stimulation: skin displays

"In short, the tactile sense can serve as an alternate information channel for selected man-machine interfaces." - Andrew Szeto [26]

Receptors in the skin can be used to carry information to the brain. Tactile (touch) displays use this fact to realize a man-machine interface. Before a new tactile display could be designed, the current limitations and possibilities of tactile display technology should be examined. An overview of the current state of research towards sensory substitution (most notably tactile displays) is presented in the following paragraphs.

Information can be sent from neurons in the skin to the CNS as a result of various types of stimulation, and body location is also known to affect display effectiveness[4]. Initial research in the field was aimed at transferring information mainly through mechanical methods. Displays consisting of an array of pins of variable height (that don't move during normal use) are only useful if they are actively explored, because without movement, adaptation masks the sensation, and no pattern recognition (information transfer) is achieved[17]. Such interactive (haptic) displays can be explored, for instance by moving a fingertip over a display surface. When voluntary exploration is not practical, displays consisting of an array of vibrating solenoids are more successful, because the skin is (and remains) very sensitive to pins making and breaking contact[17]. Currently, the most common approach is to use electrocutaneous methods. Kaczmarek defines electrocutaneous stimulation as follows: *"Electrotactile (also called electrocutaneous) stimulation evokes tactile sensations within the skin at the location of the electrode by passing a local electric current through the skin."*[5][17]. The current passed through the skin triggers afferents directly, rather than mechanoreceptors[14].

Electrotactile displays rely on electrodes instead of bulkier solenoids on the skin surface to apply stimulation, and power consumption is also reduced with the change to electrotactile methods. Average power consumption is estimated at $1\mu W/pixel$ for electrotactile displays, versus $10mW/pixel$ and $1W/pixel$ for vibrating solenoid and static (pin height) displays respectively[17]. Kajimoto notes that electrotactile methods are light, cheap, scalable, and more power efficient, in comparison to mechanical methods of stimulation[35].

The use of subcutaneous electrodes (like wire inserted into the skin) for electrotactile stimulation has also been suggested[17][36].

In 2002, Agarwal et al. suggested that the possibilities of electrostatic tactile stimulation should be explored further because of several advantages over electrocutaneous stimulation[37]. Kaczmarek et al. published more information on this method of stimulation. It is relying on electrovibration: stimulation occurs when skin is moved relative to electrodes, the actual current flowing through the skin is too small to trigger any cutaneous receptors. Instead, afferents are stimulated because of capacitive displacement (electrostatic force)[37][38]. Such a stimulator works by application of a large time-varying voltage between an electrode array and a ground plane. An insulating layer separates the electrode from the skin[37].

While electrocutaneous stimulation is about stimulation of afferents, it is also possible to stimulate efferents through the skin. Functional electrical stimulation (FES) for motor function is about making muscles contract in reaction to an electrical signal (it relies on affecting efferents, rather than actual muscle fiber), it can be used to replace muscle function and control in patients with neurological problems[39], or as an rehabilitation aid[40].

4.1 Sensory substitution: state of the art

Previous research in the field of sensory substitution was often aimed to improve the quality of life for the disabled. For instance, systems conceptually similar to Bach-y-Rita's TVSS (tactile-vision substitution system) provide the blind with an additional sense to help them perceive their surroundings, by communicating visual information from a digital camera to the user through a tactile display[5][9][35][41][42][43][44]. A high-level overview of a TVSS is shown in figure 4.1.

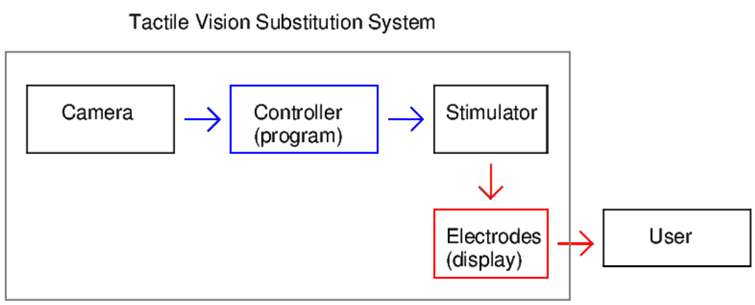


Figure 4.1: A high level overview of a tactile-vision substitution system. Red indicates stimulation current, blue indicates software control.

Examples of sensory substitution systems are presented in table 4.1.

Table 4.1: Non-exhaustive list of sensory substitution systems, information from [4], [16] and [32]. EM=electromagnetic (solenoids), ET=Electrotactile (electrodes), CG = constraint gauge.

Sensors	**Stimulators**	**Description**
5 ultrasound	Stereophonic	Sonic Pathfinder(TM), Heyes, 1984
2 ultrasound	Monophonic	UltraSonic Torch(TM), Kay, 1965
3 ultrasound	Stereophonic	Sonic Glasses(TM), Kay, 1974
3 ultrasound	Stereophonic	Trisensor(Kaspa(TM)) distributed by SonicVision Ltd.
1 ultrasound	Tactile(EM)	Mowat Sensor, Pulse Data Int. Ltd.
Accoustic (micro)	Tactile(EM)	Tactile Sound Transducer, Clark Synthesis
Camera	Tactile(EM)	Optacon, TeleSensory Inc.
Text data	Tactile (EM)	Static tactile display, Frisken et al., 1987
Graphic display	Tactile (EM)	Virtual Tactile Tablet, Boyd et al., 1990
Video camera	Stereophonic	The Voice(TM), Meijer, 1992
Video camera	Tactile(EM)	TVSS 20x20, Back-y-Rita, 1963
CCD camera	Tactile(ET)	VideoTact(TM), Unitech Research Inc., 1996
Tactile (CG)	Tactile (EM)	EVTS, up to 20 stimulators, Orbitec
CCD camera	Tactile(ET)	Tongue Display Unit, Bach-y-Rita et al., 1998

Around 1965, Bach-y-Rita and Collins started developing a tactile vision substitution system (TVSS), aimed at providing the blind with an alternative means of acquiring visual information[33]. Their experiences during the process of researching and exploring the subjects of sensory substitution and tactile displays has been described in the book "Brain mechanics in sensory substitution"[9]. In this book, optimistic expectations were presented about the future development and public adoption of devices and applications based on the principles of sensory substitution[9]. 25 years later, Lenay et al. published a comparison between the statements from the 1972 book to the actual developments in the field[32]. The most important conclusion from their publication can be illustrated by the following quote:

"As it turns out, this prediction["...the development of refined sensory substitution systems should allow many of the questions raised here to be answered...", [9]] is far from having been fulfilled: in spite of their scientific and social interest, their real effectiveness and a certain technological development, prosthetic devices employing the principle of "sensory substitution" are not widely used by blind persons for whom they were originally destined." - C. Lenay et al.[32].

Bach-y-Rita and Kercel noted in 2003 that progress in the fields of sensory substitution and (electro)tactile displays depends on the prevalence of prototypes that provide us with more insight into the mechanisms behind sensory substitution[18]. Such technologies provide great potential for the design of better, and fundamentally different types of man-machine interfaces[18].

As of this writing (2013), the situation still has not changed: the blind are still blinder than bats (because even relatively simple sonic range indicator systems are not commonly used by the blind, and full-fledged TVSS systems are even more rare, with the notable exception of the BrainPort systems from the UW-Madison lab[86]), and sensory substitution applications are generally uncommon, though even relatively crude (very low resolution) implementations, for instance used to provide crude sensory feedback, are expected to improve the usability of prosthetic limbs significantly. It might seem strange that even decades after it was proved that the human sensory system can learn new modes of perception, seemingly opening up a world of possibilities when it comes to man-machine interaction, such systems are nowhere to be found. Two separate problems come to mind: 1) the development of better (higher resolution, more efficient coding schemes, significant new findings, new areas of application) tactile displays is moving slower than expected, and 2) the commercial unavailability of products that would not require sensory substitution technology (or other forms of stimulation through electrodes, like Functional Electrical Stimulation) more sophisticated than the ones that already exist (the technology that has already been developed and tested would be sufficient for some applications, why are no products taking advantage of this?). A number of reasons for the limited commercial success of sensory substitution-based products are examined in section 5.1: Why are electrocutaneous displays still uncommon?.

4.2 Physiology of the skin

The skin contains various afferents (from receptors for perceiving pressure, vibration, temperature and pain) and efferents (motor neurons, for muscle control), situated at their respective depths in the skin. An overview of cutaneous receptors is presented in table 4.2. To effectively design a display that transfers information through the skin, it is important to note what types of nerve or receptor are to be stimulated, and which nerves or receptors should explicitly not be stimulated. The presence and density of each receptor type varies with skin type and location on body. Parts of the body that require a higher resolution of perception (like the fingertips and lips) are expected to contain higher concentrations of receptors, and neurons in the cerebral cortex are designated to process the input from such a denser population of receptors in the skin[29].

Table 4.2: Cutaneous receptors and their possible functions, adapted from [20].

Receptor	**Location in skin**	**Responds to**
Free nerve ending (practically unmyelated)	Near base of hairs, elsewhere in skin	Pain, warmth cold
Hair-follicle receptor	Hairy skin	Movement of hairs
Meissner's corpuscles	Hairless skin	Sudden skin displacement, low-frequency vibration
Pacinian curpuscles	Both hairy and hairless skin	Sudden skin displacement, high-frequency vibration
Merkel's disks	Both	Indentation of skin (pressure)
Ruffini endings	Both	Skin stretch
Krause end bulbs	Mostly in hairless skin	Unknown

In order to design a display that uses receptors in the skin to transfer information (cutaneous interface), the first step is to map the receptors in the skin to get an overview of receptor type, receptor depth and properties of the receptor signal to find the best target receptor(s) for stimulation. Receptors are organized differently in hairy or hairless (glabrous) skin. Figure 4.2 shows the locations of receptor types schematically. In hairy skin, the hair-follicle receptors add to the mechanical senses, and Merkel's disks are grouped together into the tactile disk structure in hairy skin[29]. The image presented in figure 4.2 was taken from [29]. Note that properties of the skin like hairiness and receptor contents vary wildly with locus, this effect should be considered.

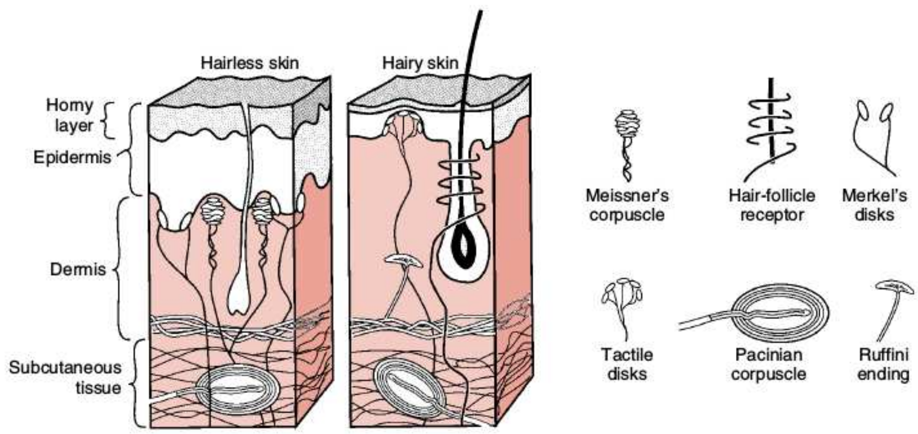


Figure 4.2: Cutaneous receptors in hairy and glabrous skin, taken from [29].

Some receptors in the skin are simply bare neuron endings (for instance pain receptors), some are elaborate neurons (Meissner's corpuscles, Ruffini endings), some are part of a complex structure. Receptors for heat and cold can be stimulated by some chemicals as well. For instance, the responses to peppers and menthol are reactions to "hot" and "cold" respectively. The reason the "hot" from peppers and acids feel like painful heat is because the type of heat receptor ("type" also refers to the interpretation of the signal in the brain!) triggered is meant specifically for indication of "dangerous" temperatures over 43 degrees C[20].

The Pacinian corpuscle detects sudden displacement of skin or high-frequency vibrations. Mechanical pressure bends the membrane of the receptor, changing its permeability to Na+ ions (influx of Na+ ions depolarizes the cell, this can lead to an action potential, (for more information see section 3.2)). Because of the physical structure of the Pacinian corpuscle (a onion like structure with a receptor cell at its core), only a sudden or vibrating stimulus can bend the membrane to activate the receptor[20].

Information from skin receptors (below the head) is communicated to the brain through 31 spinal nerves. Each nerve caries the information for receptors in a part of the skin surface (dermatome), but some dermatomes overlap (information from some skin areas might be transferred by multiple nerves). Sensory information is sent to the brain via well-defined pathways. Mechanical information is communicated via another path than pain information, pathways are important for interpretation of signals, as the context of a neural signal depends more on the context of neurons processing the information than the properties of the actual signal sent by the receptor in response to a stimulus[20].

Merkel's disks respond to "intensity" of steady pressure, and they adapt slowly. Meissner's corpuscles also respond to steady pressure, but they adapt more rapidly, therefore making them useful as velocity receptors. Pacinian corpuscles adapt very rapidly to sense acceleration, they respond to fast-changing stimuli (sudden stimuli, vibration). Rufini endings adapt slowly[8][29].

Multiple terms are used to refer to the four skin receptors relevant to tactile display research. Table 4.3 lists the names per receptor type for clarity. The functional classification of the four receptors is presented in table 4.4. They are referred to as FA I, FA II, SA I and SA II, ordering them by their respective adaptation (response) speed and resolution.

A receptor of type FA responds/adapts fast (responds to sudden stimuli), while type SA receptors respond/adapt slower. The types I and II indicate high and low spatial resolutions respectively. Type I units (notably SA I) respond strongly to the pressure of narrow edges on the skin. SA II are also directionally sensitive and they respond to stretch[45].

Table 4.3: Overview of mechanoreceptor names and classes [45][46].

Receptor name	**Know as**	**Also known as**
Meissner's corpuscles	FA I	RA, QA
Pacinian corpuscles	FA II	PC
Merkel's disks	SA I	SA I
Rufini endings	SA II	SA II

Table 4.4: Properties of mechanoreceptor types in hairless skin of the hand [45].

Receptor type	**Response speed**	**Response type**	**Area**	**Border**	**Distribution**
FA I	Fast	Not static	Small	Sharp	43%
FA II	Fast	Not static	Large	Obscure	13%
SA I	Slow	Static	Small	Sharp	25%
SA II	Slow	Static	Large	Obscure	19%

Because the skin receptors react to their respective stimuli, signals from a specific receptor are interpreted to be caused by the phenomenon expected to activate that specific receptor, leading to the perception of the corresponding (interpreted) feeling. The reason a signal from a receptor in the skin of the hand feels like a stimulus located on the hand is simply training, if the connections from neurons to their respective receptors (located in two separate parts of skin) were to be switched, the brain would interpret stimulation of the first location as a stimulation to the second location (because signals from that neuron are expected to be signals sent by receptors in the second location!).

To design a display that uses receptors in the skin to communicate (encoded) information, it can be useful to do so selectively. Kajimoto et al. described a method to stimulate the four mechanoreceptors (or the afferents connected thereto) individually using specific electrical stimulation wave shapes and electrodes[46]. He writes that an electrocutaenous display that stimulates receptors selectively could emulate all familiar sensations (pressure/intensity, acceleration, velocity, and more complex interpreted sensations) on the skin, he compares the individual receptors to color channels ("tactile primary colors") in visual displays[47].

Each receptor has an activation function based on the physical properties of the receptor type (also receptor density and size), and the location (depth and orientation) in the skin. By using an array of electrodes, Kajimoto et al. attempt to direct the distribution of current (they also distinguishes anodic and cathodic current), and experiments show that three modes of specific stimulation are feasible[46][47]. An overview of stimulation modes described by Kajimoto et al. are presented in table 4.5.

In RA mode, vertical axons are stimulated selectively by means of anodic current through a single electrode, causing a concentrated, deep current distribution under the electrode. The other two modes rely on weighted current distribution controlled by an array of multiple electrodes. By varying the relative magnitude, and direction of the current flow, SA I can be activated selectively, or together with FA II. FA II can not be stimulated selectively, but this is not a problem. Under normal (mechanical stimulation of the skin) conditions, SA I is always activated together with FA II[46].

Table 4.5: Selective activation of mechanoreceptors [46][47].

Mode	**Targets**	**Sensation**	**Current polarity**
RA	FA I	vibration	anodic
SA I	SA I	pressure (knife edge, soft, rubber)	cathodic
PC	FA II, SA I	shifted vibration sensation	cathodic

Data in table 4.6 shows important properties of the four types of mechanoreceptor in the skin. The receptive field (field of view of one receptor) is shown, the range of stimulus frequencies the receptor responds to (and what range the receptor type is most sensitive to), and the minimal skin deformation required to trigger the receptor[4].

Table 4.6: Overview of mechanoreceptor properties[4][17].

Class	**Receptive Area (med.)**	**Frequencies**	**Most sensitive**	**Min. deform. (med.)**
FA I	1-100 mm^2 (12.8)	10-200 Hz	20-40 Hz	4-500 μm (13.8)
FA II	10-1000 mm^2 (101)	40-800 Hz	200-300 Hz	3-20 μm (9.2)
SA I	2-100 mm^2 (11.0)	0.4-100 Hz	7 Hz	7-600 μm (56.5)
SA II	10-500 mm^2 (59)	7 Hz		40-1500 μm (331)

An interesting observation is that the perceived quality of a stimulus changed radically depending on stimulation current. Table 4.7 shows the effect on the qualitative feeling resulting from current pulses of various magnitude. Although the type of feeling that is caused by stimulation depends on the subjective interpretation of the test subjects, the perceived effects are not presented as though they would not be reproducible across subjects[46][47]. One additional effect is interesting to note: in SA I mode, the interpreted type of stimulus changes from "knife edge" to "elastic rod" if the finger is moved[46][47]. This is because the interpreted qualities rubber and sharp edge are percepts build from integrated sensory information, and in this case, a feedback loop is playing an important role. The brain has learned to interpret a certain pattern of sensor information, integrated temporally to known what sequential intensities of stimulation to expect from the surface of the finger, in the case of pressing on a knife edge. As long as the finger stays still, selective stimulation (SA I mode) is interpreted as an edge, but the pattern of temporally and spatially integrated information as a result of a finger moving over an SA I mode stimulus is more similar to the input expected to be caused by a rubber rod.

Table 4.7: Effect of SA I mode stimulus current on perceived type of feeling, adapted from Kajimoto et al. [46][47].

Central electrode current	**Description**
0.2 mA	a tiny tremoring sensation
0.4 mA	pressure in the shape of the electrode, line electrode feels like the edge of a knife
0.6 mA	new vibratory sensation, together with pressure
$>$1 mA	stronger vibration, masking pressure sensation

Stimulator and electrode size, bandwidth, wearability, and usability have to be considered to select the best location on the body to place stimulation electrodes (or an electrode array). Practical bandwidth depends on skin type (receptor types and densities), training, and stimulator properties like encoding scheme, wave shape, and electrode properties.

Resolution of the skin (mechanoreceptor density) is often quantified using a two-point measurement. Two points of stimulation on the skin are positioned in such a way that they are as close together as possible, under the condition that the human subject is still reporting the perception of two separate points of stimulation. Table 4.8, adapted from [4], shows the two-point discrimination threshold for potential stimulation sites on the skin. References to the publications this data is based on are present in the original table published by Kaczmarek and Bach-y-Rita[4]. However, the actual spatial resolution of the skin is not as limited as the two-point measurements suggest. There is evidence that skin receptors are able to detect very small movements. Kaczmarek et al. suggest an approach based on time-division multiplexing that increases the practical spatial resolution of the skin significantly[48]. The two-point minimal discrimination distance varies over time, and it can be improved by training[4]. The two-point method might give an indication of relative receptor densities, but as the table shows, (especially the case of the back) static stimuli and electrotactile stimuli may yield very different results. It is said that static stimuli are generally very hard to perceive in comparison to non-static ones[32].

Table 4.8: Simultaneous two-point discrimination threshold (mm) adapted from [4] and [35].

Body location	**Static touch**	**Vibrotactile**	**Electrotactile**
Fingertip	3	2	<7
Palm	10	?	8
Forehead	17	?	<3
Abdomen	36	?	10
Forearm	38	?	9
Back	39	11-18	5-10
Thigh	43	?	10
Upper arm	44	?	9
Calf	46	?	9

The skin also contains a number of receptors for pain, called nociceptors. Pain receptors in the sin are free endings of myelinated and unmyelinated neurons, and they are present everywhere in the skin. In fact, they are present in higher concentration than other types of receptors. However, the threshold for activating a pain receptor is usually much higher (probably due to differences in the cell membrane[29]) in comparison to other cutaneous receptors. In practice this means that the other cutaneous receptors can be stimulated by a 'normal' intensity (mechanical) stimulus without triggering the pain response, while an intense stimulus that would be strong enough to damage tissue is interpreted as pain[29]. Again, input to the brain is only interpreted as "pain" if the input arrives through a channel expected to carry signals from receptors that are only to be triggered in reaction to phenomena that cause tissue damage (and therefore, require immediate attention). Commonly, superficial pain has two components: The first response is a short sharp, localized sensation, the second component starts after a delay of about 1 second, it manifests as a dull and more diffuse pain that lasts longer than the initial pain[29]. The two different pain responses are a result of the triggering of separate subtypes of pain receptor[29].

Vibrotactile displays physically deform the skin, triggering the mechanoreceptors the "natural" way, but when stimulating the skin electrically, it becomes harder to trigger mechanoreceptors without accidentally triggering pain receptors too. The dynamic range of electrotactile stimulation is commonly defined as the ratio between the smallest current pulse a subject is able to perceive, and the strongest stimulation that does not cause a response labeled as "pain"[49]. Practical (commercially available) electrotactile displays are expected to deliver data by only triggering mechanoreceptors, without triggering any pain receptors. To complicate matters, pain receptors exhibit less adaptation to stimuli than mechanoreceptors (this is to be expected, considering their respective functions). The subject of sensory adaptation is explored further in section 4.7.

4.3 The electrode-skin interface

Electrotactile stimulation triggers neural signals, resulting in localized sensations, by passing an electric current through the skin through stimulation electrodes. The resulting electric field in tissue past the horned layer of the skin affects the (myelinated) afferent fibers directly (activation of the receptor the afferent connects to is not necessary)[5][17][50][51].

Kaczmarek et al. state: *"Subjects describe electrotactile sensations qualitatively as tingle, itch, vibration, buzz, touch, pressure, pinch and sharp and burning pain, depending on the stimulating voltage, current, and waveform, and the electrode size, material, and contact force, and the skin location, thickness, and hydration."*[17].

Sensation threshold, perceived stimulus intensity, and qualitative feeling caused by electrotactile stimulation depend on the major factors of location on the body (skin type, receptor content), stimulus waveshape, electrode shape and size, and stimulus current[50][52]. The electrode-skin interface covers the electrodes, the contact surface between the electrodes and skin, and the parts of the skin involved in conducting the stimulus. In order to stimulate the mechanoreceptor afferent, a current must pass through the high-resistance stratum corneum (horned layer of the skin)[53], but the resistance of the skin varies wildly with location on the body, hydration, mechanical contact, and dirtiness[17][25]. The resistance of the high-resistance part of the skin changes from 50-200 KΩ for dry skin, to about 10 KΩ or less for hydrated skin[25]. A thicker layer of skin (like the skin on the fingertips) also leads to a higher resistance, and the resistance of the skin goes down if the skin is cleaned properly.

Models have been conceived to approximate the electrical characteristics of the electrode-skin interface. The first-order model of the electrode skin interface commonly accepted [4][5][52][53][54] is shown in figure 4.3.

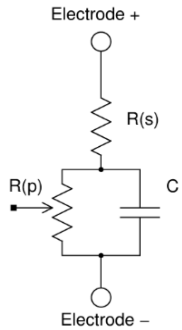


Figure 4.3: A first-order model of the electrode-skin interface

Control of the electrotactile sensation is complicated because of the many contributing factors, especially the ones that are not constant over time. The effects of sensory adaptation (the phenomenon that the perceived intensity of a stimulus is reduced over time) will be ignored for now, it will be covered in section 4.7. The skin resistance may vary over time, and it changes in reaction to the electrical stimulus. For instance, the resistance of the electrode-skin interface decreases with increased stimulation current, in a non-linear fashion. Kaczmarek and Webster compared a number of mathematical models to predict the relationship between stimulation current and the resistance of the electrode-skin interface, and they presented the three possible models shown in figure 4.4[54]. The commonly accepted model (first-order exponential) is the middle one (b) in figure 4.4.

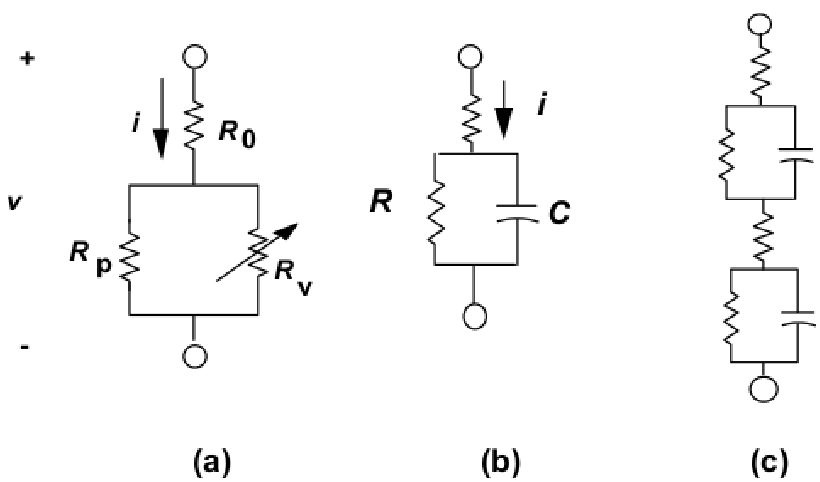


Figure 4.4: Three suggested models, taken from [54]. (a) Nonlinear static resistance model. (b) Single exponential dynamic model. (c) Double exponential dynamic model.

Figure 4.5 shows the fit of the relatively simple model (a) to data showing the resistance of the electrode-skin interface as a function of stimulation current, where the model parameters (resistor values R_0 and R_p) have been determined empirically[54]. Kaczmarek and Webster conclude that the rise and fall phases are modeled better by two different models: the rise phase is modeled best by $v(t) = V_m(1 - e^{-t/\tau})$ (model (b)), while the fall phase is better modeled by $v(t) = V_{m1}e^{t/\tau_1} + V_{m2}e^{t/\tau_2}$ (model (c)), as shown graphically in figure 4.5. Figure 4.6 shows how well the first order (b) and second order (c) models fit actual data of the falling phase. Note that the second order model fits the data better. Because the type of model and model parameters have to change to model both rise and fall phases adequately (which they deem "unphysiological"), they concluded that the phenomenon is likely better described by a model that includes time-varying parameters.

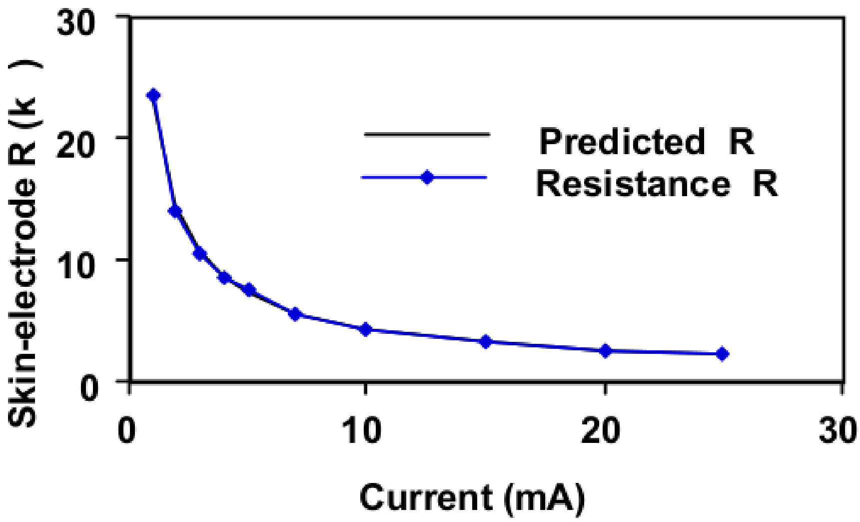


Figure 4.5: Resistance R (in KΩ) of electrode-skin interface, as a function of stimulation current (the plots of "Predicted R" and "Resistance R" overlap). Taken from [54].

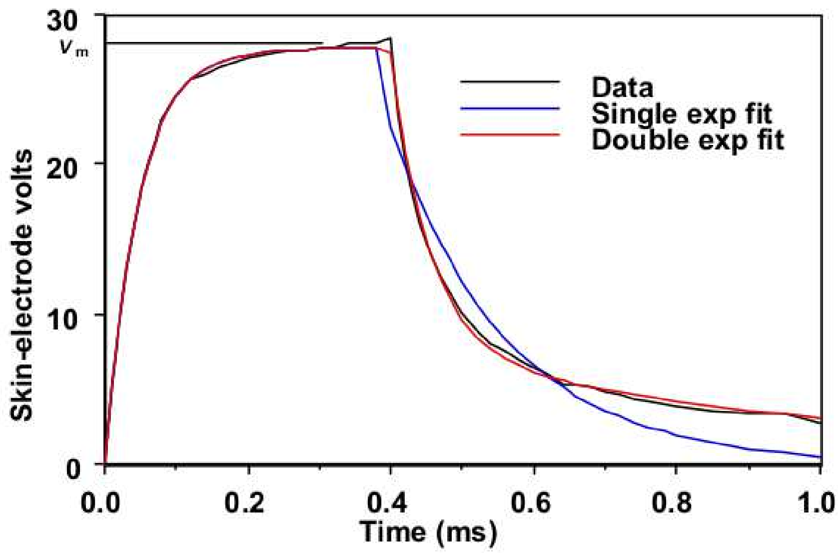


Figure 4.6: Skin-electrode voltage, plot of two mathematical models and data, taken from [54].

One of the most important stimulation parameters to influence the perceived intensity of an electrical stimulus is current, and it should be controlled adequately[53]. The current can not be controlled using constant-voltage stimulators, because the resistance of the electrode-skin interface reacts to a change in current, causing an instability (if the resistance changes, the current also changes, causing another change in resistance)[53]. Therefore, a stimulator should use a constant-current supply. However, the skin is not homogeneous, and some spots on the skin have radically lower resistance. The distribution of current becomes a factor, the current density is not divided equally from the electrode surface. A problem that is known to occur is that current taking a shortcut (probably through sweat ducts) produces a sharp stinging pain (this situation is to be avoided)[5][51]. Even though the total current flowing from the electrode is constant (that is the idea behind a current source), high density current is localized at low-resistance paths, and because of the positive feedback loop that causes path impedence to drop with increased current, the effect increases over time (current collapse). The current collapse phenomenon leading to painful pricking sensations is reported to occur only as a result of anodic stimulation[5][51]. Considering findings reported by Kajimoto et al. on the subject of selective activation of cutaneous receptors[46][47], it is quite possible that both anodic and cathodic stimulation are prone to the current collapse phenomenon, but anodic stimulation is more efficient at activating pain receptors than cathodic stimulation.

Kaczmarek et al. found that the electrotactile stimulation threshold changes periodically, they state that the commonly observed threshold variations over time are not due to random noise[52]. The variations exhibit a cyclical behavior, with a period of 3 to 10 minutes. It is concluded that the cause of the variations is likely not related to phenomena in the electrode-skin interface[52].

Variations in skin hydration (and therefore, skin resistance) complicate the accurate control of the (intensity and quality) of sensations triggered by electrotactile stimulation. According to Jayaraman et al., the electrotactile sensation changes significantly and unpredictably because of this effect[50]. Because ambient humidity impacts sweat gland activity and skin hydration, they examined the impact of humidity on the impedance of the electrode-skin interface by controlling the humidity of the air both for the space between two electrodes (coaxial, concentric ring electrodes), and outside the electrodes. It was found that the inside humidity (between the electrodes) has a significant impact on skin resistance (higher humidity leads to less skin resistance), while humidity outside of the electrodes does not matter[50].

4.4 Encoding of information for electrocutaneous stimulation

"Tactile perception of sensory information requires that the information be converted (or encoded) into stimulating waveforms which are clear, comfortable, and easily understandable." - A. Y. J. Szeto and F. A. Saunders [25]

Numerous types of electrotactile stimulation waves shapes exist, and many different ones are able to invoke a sensation in reaction to a stimulus[4]. Such waves have a number of parameters, and information can be encoded into a number of them, notably stimulation current(amplitude modulation), pulse frequency (frequency modulation), pulse duration (or pulse width, frequency modulation), energy per pulse (amplitude modulation), or gated bursts (low frequency bursts of high frequency pulse trains, frequency modulation) [4][25][34]. Figure 4.7 shows the properties of a square wave signal that can be used to describe all common stimulation wave shapes described in literature[55].

Some wave shape parameters do influence the perceived quality of a stimulus (and affect adaptation rates and possible chemical reactions at the contact point between electrodes and skin), but they are not used to carry information. A stimulation wave can be either functionally biphasic or monophasic, and monophasic waves can also be capacitively coupled (net zero-DC current), waveshapes are shown in figure 4.8. The stimulation can be either cathodic or anodic (the polarity of the center electrode during the first phase) [4].

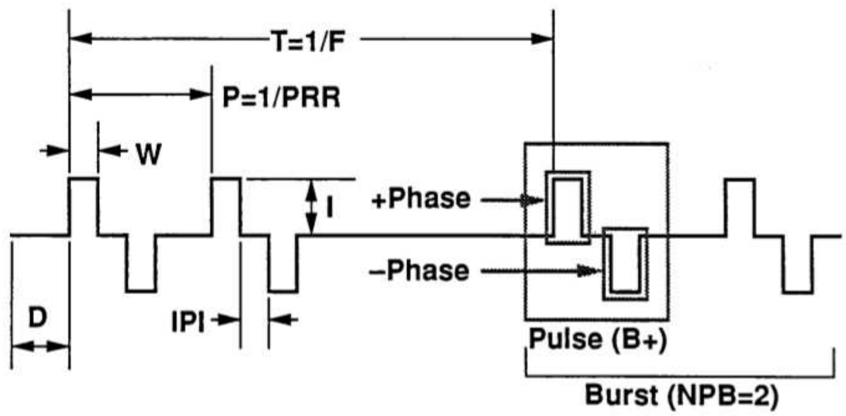


Figure 4.7: Electrotactile waveform parameters, taken from [5], D=delay,W=width,IPI=interphase interval,I=current,T=time between bursts,F=burst repetition frequency,P=period of pulse repetition, PRR=pulse repetition rate,NPB=number of pulses per burst.

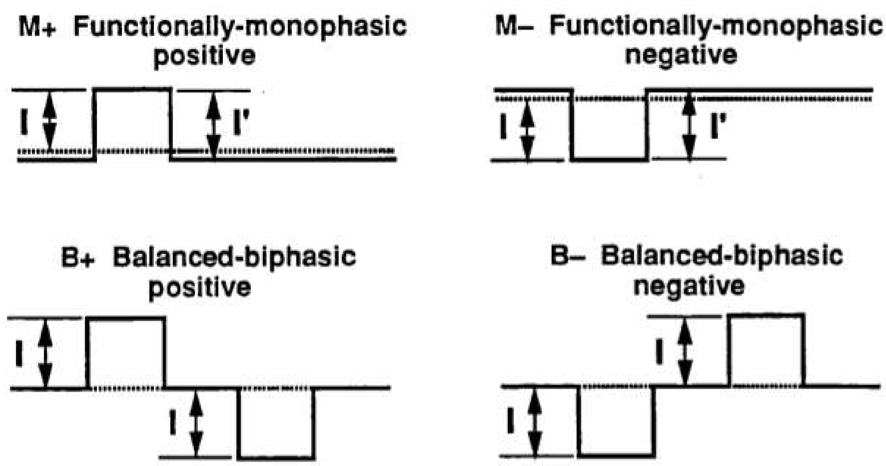


Figure 4.8: Shape of functionally monophasic (zero-DC) and balanced biphasic wave shapes, taken from [5].

Szeto included gated burst codes in his comparison of code effectiveness[31][34]. Gating bursts is about nesting various frequency signals, practically by logical AND-ing multiple (square) waves (of different frequencies), figure 4.9 shows this principle. Normally, a low-frequency train of pulses would be "high" for the duration of the pulse, and "low" for the time between the pulses, but during the "high" phase of gated bursts, the signal is alternated between "high" and "low" at a higher frequency. Figure 4.9 shows a gate burst wave form where the number of low-frequency pulses per second is constant, and information is encoded in the number of high frequency pulses per burst, comparable to encoding information in pulse width of a simple square wave signal. Szeto also tested encoding of information of the number of bursts per second (with a fixed number of pulses per burst, called burst duration modulation, called burst rate modulation), comparable to pulse rate modulation of a simple square wave signal[31][34].

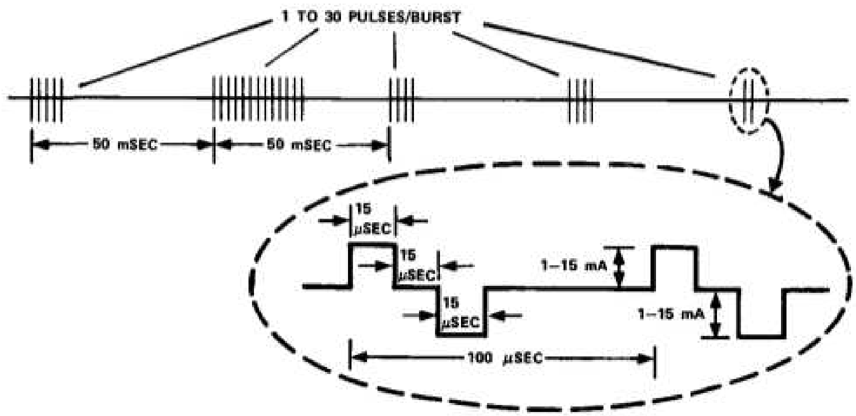


Figure 4.9: Gated bursts, taken from [31]

Sachs et al. found that if the information is encoded as intensity (by varying pulse rate), a range of sensations may be generated without pain[56]. Szeto found that the perceived intensity as a result of a stimulus train of a certain frequency depends primarily on the charge per stimulation pulse (pulse width*pulse amplitude)[26][17]. According to Szeto, an electrocutaneous stimulator (current source) capable of supplying pulses up to 15 mA, could span the entire dynamic range with pulse widths between 30 μsec and 1000 μsec[26]. His conclusion is that the pulse width of a pulse train of current pulses should decrease as the pulse rate increases to control the total charge delivered, in order to control stimulus intensity. Aldayel et al. found that the perception threshold could be stabilized under certain conditions (most importantly: dual channel stimulation with at least 5 pulses/second, interleaved time between electrode signals should be longer than 500 μsec)[57].

The Just-Noticable Difference (JND) is a (crude) measure for channel sensitivity[17], a higher number of JNDs means the channel is more sensitive. The JNDs of various tactile stimulation methods are presented in table 4.9, the majority of JND measurements presented in the table are the result of electrotactile stimulation (with surface electrodes, except for the ones marked explicitly as "subdermal"), except for the ones marked with (M) or (VT), for mechanical and vibrotactile stimulation respectively. The table was taken from [17]. The factor limiting JNDs in these experiments are not likely to result from limits in bandwidth of the skin, instead they result from CNS processing capabilities (lack of training)[17].

Table 4.9: Just-Noticable Differences of Electrotactile, Vibrotactile (VT) and mechanical pressure (M) stimulation [17].

Location	Variable	JND (%)
Abdomen	Pulse width	>6
Arm	Current	9-29
Arm (Subdermal)	Current	8-42
?	Current	2-6
?	Frequency	>2
Arm	Frequency	15-30
Arm (Subdermal)	Frequency	10-25
Abdomen	Current	3.5
Abdomen	Number of pulses	10
Palm	Frequency	19-24
Arm	Frequency	16-38
Arm	Pulse Width	36-46
Several	Pulse width	8-10
Several	Current	8-10
? (VT)	Frequency	5-10
Arm (VT)	Frequency	20-25
? (M)	Pressure	20

Table 4.10 shows the number of JNDs is higher if stimulation current is varied in comparison to a variable frequency, but stable current. This phenomenon is explained by Kaczmarek as follows: if current is increased in small steps, sensory adaptation causes the stimulus to decrease in perceived intensity over time, but this effect does not occur as much if frequency is changed[4][17]. Note that the number of JNDs are not the same as number of discrete steps that can be identified reliably, those are estimated to be 4-5 for vibrotactile stimulation, and 6 for electrotactile stimulation[4][17].

Table 4.10: Number of discernable levels of stimulation for electrotactile and vibrotactile (VT) stimulation [4].

Location	Variable	Number of levels
Abdomen	Current	59
Abdomen	Current	32
Palm	Frequency	13
Arm	Pulse energy	8-16
Arm	Frequency	6-8
Arm	Frequency	11
Arm (Subdermal)	Frequency	16
? (VT)	Amplitude	15

Combinations of parameters can be used to encode information in multiple channels[58], through a single stimulation electrode, but complex interactions between wave shape parameters and the perceived stimulus may exist, that could result in a situation where the perceived effect from one channel depends on (changes with) the other channel. If these effects are not taken into account, the encoding of data into multiple channels (in a single waveshape, delivered through a single electrode pair) becomes impossible[26].

Szeto and Lyman used a tracking task to measure the effectiveness of a number of electrotactile codes[34]. Subjects have to estimate (track) the "location" of a dot encoded in a stimulus waveform continuously. It was expected that a subject could only use a electrotactile encoding of good quality to achieve good tracking task performance[31][34][59]. Multiple electrodes can also be used to transfer the same signal through each electrode to improve accuracy of data transfer[31][34].

In one of Szeto's experiments, he used a two-channel tracking task to test the response to various electrotactile codes to transfer information through two electrodes simultaneously: the subjects had to track two independent stimuli simultaneously[31]. It was found that the same electrotactile codes resulted in the best tracking performance, for single-channel as well as dual-channel stimulation[31], and that codes through multiple electrodes are significantly more efficient than any single-electrode code he examined[34].

Subjects experienced biphasic stimulus waveforms as being more comfortable than monophasic waveforms[34], but performance of codes transferred with monophasic wave forms is superior[31][34]. Subjects reported that biphasic stimulation waveforms required more mental effort to interpret than monophasic stimulation waveforms[34]. Also, spatial codes using multiple electrodes were reported to be easier to use than single-electrode codes, and they don't seem to suffer from sensory adaptation[34]. Single-electrode codes that use frequency modulation to encode information were found to be better than codes relying on intensity modulation, for both monopolar (functionally monophasic and bipolar (balanced biphasic) stimulation waveforms[31][34]. During his experiments, Szeto found that the ability to discriminate frequency was not yet saturated at stimulation frequencies of 40-50 Hz[59].

Multiple electrode codes might be more efficient to display a specific value to a user, but for some (simple feedback) applications, communication of data through a single electrode might be preferable. To maximize the information rate through a single electrode, information may be encoded in two channels per electrode: both frequency and intensity could be modulated separately[26]. Szeto's method for encoding two channels of information in a waveform through a single electrode depends on modulating frequency and intensity of the stimulus independently[26], this principle is explained in detail in the section 4.5. Bach-y-Rita and Kaczmarek stated: *"The best way to encode information with a multidimensional stimulus waveform was through modulation of the energy delivered by the stimulus."*[10].

Although the CNS responds relatively slowly to tactile input (200 ms, much smaller changes in stimulus can still be perceived and processed(<1 ms)[17], this is similar to the observation that the smallest perceptible movement on the skin is much smaller than would be expected from two-point measurements[4] (for details, see section 4.2 and table 4.8). Kaczmarek reached the conclusion the human somatosensory system uses multiple types of temporal processing, with time constants ranging from 0.2 ms to greater than 60 s[4].

The sense of touch humans are used to is a result of subconscious spatial and temporal integration of cutaneous and kinesthetic information[4], for instance, if a finger is tracked over a textured surface, the skin of a fingertip could be used to explore the surface, the CNS integrates the stimuli from surface features over time and movement, to form a detailed mental model of the texture of the surface[4].

Bach-y-Rita states the following, based on G.A. Millers work[4][9]: *"There are several ways by which the limits of the channel capacity for absolute judgments can be exceeded."* He lists three ways to do so:

1) we can make relative, rather than absolute judgments
2) we can increase the number of stimulus dimensions
3) we can present the task in a way that permits the user to make a sequence of absolute judgments over time

Point 3 relies on the assumption that memory is a very important factor in the interpretation of input data[4]. Absolute judgment is limited by the amount of information per stimulus (bits of data), human immediate (working) memory is limited to a number of simultaneous "chunks" (similar to CPU registers), the number of available chunks seems to be independent of the size of the data (in bits) per chunk[4].

Because the practical resolution of current tactile displays is limited, highly detailed graphical representations can not be displayed integrally. High resolution information may still be presented through such a display, if the data presented depends on movement. Because the user is able to control the movement of the "slot" displayed, the CNS is able to reconstruct the high resolution data from separate chunks[4].

Another way to take advantage of the temporal integration capabilities of the CNS is time-division multiplexing: time-division multiplexing is a technique to split and feed data through the skin in smaller blocks, the CNS reconstructs the original data by means of temporal integration. To display a 128x64 pixel image from a camera on a tactile display (as part of a TVSS), Kaczmarek et al. divided the image into 6x24 blocks that are displayed sequentially on a fingertip vibrotactile display[48][60]. Changing the mapping of pixels to electrodes dynamically, based on movement or position of the user might yield great advantages in perceived resolution over mapping camera pixels 1-1 to display actuators[48][60], but this has not yet been verified experimentally[K. A. Kaczmarek (personal communication, January 10, 2014)].

A tongue display unit exists that uses a 144 tongue electrode array to display data[44]. The array (12x12 electrodes) is divided into four blocks of 6x6 electrodes, and during stimulation, all electrodes in a block are activated sequentially. Four electrodes (one per block) are active simultaneously, the electrodes in each block are raster-scanned. The inactive electrodes are used as the return path, so it is important not to have adjacent active electrodes at any time, as this would disturb the current distribution (and therefore, the perceived stimulus intensity and quality)[44].

4.5 Dynamic range

The dynamic range of an electrocutaneous display is effectively the ratio between the smallest perceptible stimulus, and the biggest stimulus below the pain threshold[4][49]. The dynamic range of the senses of vision and hearing are 70 dB and 120 dB respectively[4]. The dynamic range of electrotactile stimulation is reported to be 6-20 dB[5], vibrotactile dynamic range is estimated at 40 dB. An important reason the practical dynamic range of electrotactile stimulation is smaller is likely due to pain responses, and if pain could be minimized, the effective dynamic range of electrotactile stimulation could be increased[51]. Information from the normal human senses can be interpreted as a stimulus that is strong or weak, without pain, but the sensations caused by electrotactile stimulation are easily perceived as painful because of improper stimulation waveforms or electrodes[49]. The perceived sensations of electrotactile stimuli are reported to be either of vibratory or stinging quality, and the amount of stinging limits the dynamic range[49]. It is also reported that electrode geometry and electrode location can have a significant impact on pain[4][5], and experience is also a significant factor, as experienced subjects are able to tolerate at least double stimulation intensities in comparison to untrained subject[4].

The dynamic range ratio of a tactile display is unlikely to match that of a sensor. For instance, the dynamic range of a camera (as part of a TVSS) is much higher than the electrotactile dynamic range 6-20 dB[4]. This should be solved by an appropriate scaling function[4].

The traditional way to measure dynamic range of electrotactile stimulation depends on current: the dynamic range is said to be the ratio between the minimal current required for a perceivable stimulus, and the minimal current required to reach the pain threshold. The I_p/I_s ratio is misleading because the measured currents are electrical properties that do not give any insight into the actual stimulus intensities experienced by subjects, and optimizing the I_p/I_s ratio of a stimulation waveform is not guaranteed to lead to the most effective stimulation waveform. A method to define and measure electrotactile dynamic range better, by focusing on perceived stimulus intensity instead of current, is presented by Kaczmarek et al.[49].

The (subjective) stimulus intensity of a train of stimuli is raised with increased pulse width, current, and pulse rate (frequency). Pulse rate impacts the perceived intensity relatively little. In the case the stimulus wave consists of gated bursts, more bursts per pulse also increase perceived intensity of a stimulus[4][17]. Szeto reported that the perceived intensity (probably depending on "charge per pulse") of a stimulus could be controlled separately from the "quality" of the stimuli, if pulse phase width (W, in microseconds) and frequency (F in Hz) are varied according to the relationship: $logW = 2.82 - 0.412(logF)$[26].

The higher the stimulus intensity, the better subjects performed in a multi-electrode pattern recognition tasks, suggesting a trade-off between spatial information (image resolution) and per-electrode stimulus resolution for graphical electrotactile displays[61].

4.6 Painful sensations

It has proven to be difficult to stimulate mechanoreceptors electrically, without also causing a sensation of pain as a side effect (often because of accidental stimulation of nociceptors). Though the perception of pain is subjective, three types of pain are commonly discerned[4]:

1) Prickly sensations, at all stimulation levels
2) Sudden stings, at low-to-moderate stimulation levels
3) Burning sensations, at high stimulation levels

On hairy skin, prickly sensations and sudden stings can be avoided by using electrodes with a surface of a about 10 mm^2, provided the contact between electrode and skin is not (partially) broken[4], for instance by using conductive gel, or by allowing the buildup of sweat between the skin and electrode to ensure the entire electrode surface is in contact with the skin.

High resolution tactile displays require many electrodes, and because usable skin surface is limited, electrodes can not be very large. It is known that stimulation through small electrodes suffers from a limited dynamic range, because stimulation through small electrodes is often perceived as painful[4][62]. Poletto presented a method of reducing pain, specifically for stimulation through small (<1 mm diameter) electrodes[62]. The principle behind depolarizing pre-pulses is that a long sub-threshold pulse right before a stimulation pulse could reduce the pain threshold. A polarizing pre-pulse as weak as -10 dB relative to the pain threshold was reported to lower the pain threshold significantly (as indicated by the chance a stimulation pulse was perceived as painful)[62]. The effect of pre-pulses on the pain threshold may vary for longer and shorter pre-pulses and stimulation pulses[62].

Dynamic range of (electro)tactile stimulation is also decreased because of sensory adaptation, as explained in the next section.

4.7 Sensory adaptation

The perceived intensity result from a continuous stimulus (or train of stimuli) decreases over time, because of an effect called sensory adaptation[4]. By this mechanism, the nervous system removes background noise, or is able to ignore unimportant (redundant) data from sensory input. Resulting perceived intensity from electrocutaneous stimulation of constant intensity is reported to increase in intensity first, reaching a maximum intensity within a few seconds (likely due to temporal summation), but after a time (ranging from minutes to hours), the perceived stimulus intensity drops again due to adaptation[25].

Not all types of stimuli cause sensory adaptation at an equal rate. For instance, a user can not interpret input adequately from a static (pin height) stimulator array without moving the skin over it, as the non-moving stimuli are labeled "redundant" and discarded through the sensory adaptation mechanism[9], but vibrotactile arrays (vibrating solenoids) suffer much less from the effects of sensory adaptation[4]. Szeto and Saunders reported the effects of electrotactile wave characteristics on adaptation[25]. Sensory adaptation occurs faster in reaction to a higher frequency stimulation waves than lower frequency ones, for instance, a pulse rate of 10 Hz does not lead to any obvious adaptation, but 1000 Hz stimuli fall near or below the threshold within seconds[25]. It is likely that sensory adaptation is an important reason "slow" electrotactile codes (1-15 Hz pulses) are reported to be more effective than "fast" electrotactile codes (bursts of up to 10KHz)[31][34]. The closer the stimulus intensity is to the threshold of just being able to perceive the stimulus, the faster it is ignored by the sensory system[4]. Biphasic stimulation waveforms lead to faster adaptation than (functionally) monophasic waveforms[25][34].

If sensory adaptation is indeed a mechanism to remove redundant sensory input it is to be expected that continuous unchanging pulse trains are ignored. However, this does not necessarily mean that higher pulse rates would still lead to such sensory adaptation if a higher informational content was provided, the sensory system compresses incoming information when possible, higher information content can not be compressed as much. Why this hypothesis is hard to test is explained further in section 5.3, but there are indications that higher informational content reduces adaptation: modulated pulse trains (pulses of pulses, for instance bursts of 500 Hz pulses, gated at 25 Hz) suffer less from adaptation[17].

If perceived intensity is used as a channel for communicating data through the skin (if information is encoded in variations in perceived stimulus intensity), sensory adaptation becomes a problem when perceived intensity of a stimulus is unpredictable. However, if the perceived intensity of a stimulus would be predictable, the actual stimulus intensity could be increased over time to compensate for sensory adaptation.

5 Discussion

Even though the principles behind information transfer through electrocutaneous displays have been researched for over 135 years[88], such displays have not yet become common commodities. In the following paragraphs, a number of reasons for this will be examined. Published opinions on this subject will also be discussed. A better understanding of the possibilities and limitations of current sensory substitution technology allows a more effective approach to designing new types of interfaces. Interface types that consider the strengths and weaknesses of both the man and machine sides of the interface could obviously be more efficient in translating between the two, in comparison to the "traditional" interfaces commonly available. A new approach to man-machine interface design might lead to better interfaces, that can take full advantage of the possibilities that exist as a result of the plasticity of the human brain.

5.1 Why are electrocutaneous displays still uncommon?

A publication by Lenay et al.[32] lists a number of reasons that might contribute to the current situation: the limited spread of technology based on the principle of sensory substitution. They want to understand why sensory substitution systems have not yet become common commodities, even though it has been proven repeatedly that blind people can use tactile vision substitution systems (TVSS) to orient themselves and recognize objects. Lenay et al. make the point that the concepts associated with the term "sensory substitution" might not be sufficient to describe what is actually happening. Because "there is no perception without action", the systems has to include some sort of a feedback loop: the system has to go beyond the simple feeding of data through another sensory channel. In the case of a TVSS, the subject requires control over the position of the camera in order to create a feedback loop. Therefore, they propose to call a TVSS a "sensori-motor substitution" instead. Bach-y-Rita's work[9] shows that "a mere sensory substitution is of little use"[32]. They acknowledge that proof of the existence of human brain plasticity and the mechanisms that allow humans to recalibrate sensory input is major discovery in itself. Such a discovery incites further exploration.

Lenay et al. note that the term "sensory substitution" and the way it is presented gives rise to certain unrealistic hopes and expectations in potential users of the device. Visually handicapped users indicated that their new sense (TVSS) were working, on a basic level. However, their reaction was one of overwhelming disappointment, because the properties of the sense of vision provided through the TVSS are very different from the old sense of vision they expected to regain, and the new visual input available to them is deemed of inadequate quality to fulfill their wishes of "being able to see again". The problem is not about being able to orient themselves, or sensing the proximity of objects, but about the "joy" of visual experiences that used to be provided by their lost visual sense. The input provided through the TVSS is closer to an additional sense (a way to perceive the world in its own right), than to a replica of an existing one (like their lost sense of vision), that is why Lenay et al. think the term "substition" is unfortunate[32]. What is missing is referred to as the "qualia". In the process of experiencing life, much more is learned and remembered than skills or bare pattern recognition abilities, experience is also about associative memory, causing certain patterns input to invoke memories of previous experiences, thoughts, and emotions. Apparently, the new input feels like a cold and empty space. Objects perceived through the TVSS are devoid of any (emotional) associations, and new associations will have to be formed over time (by experiencing the world through the TVSS)[32].

Lenay et al. note "ergonomic constraints" as another limiting factor: prosthetic devices that hinder movement or are otherwise impractical are not likely to be a commercial success, and devices requiring heavy batteries that need to be charged every ten minutes are probably not considered sufficiently user friendly in most situations. Thus, systems need to be designed to be "light and autonomous", easy to "put on, or take off", and the systems should not be fragile. It should not break easily as the user will depend on it[32]. They also note that the device should not make the user look more handicapped, and *to avoid the user being perceived as a "technological monster".*[32]. One important aspect is the cost of the device, a TVSS is said to be expensive, at 45000 US dollars for a VideoTact device, in 2003[32].

Bach-y-Rita and Kaczmarek acknowledge that a number of problems exist that cause the delayed commercial availability of sensory substitution-based devicese: *"Man-machine interface problems have limited the development of practical vision substitution systems and other instrumentation developed to interface with the skin."*[10]. They present a design for a tongue stimulation unit that offers solutions to some of those problems. The primary goal is stated to be the design of a tactile display system that is "practical and cosmetically acceptable". The design consists of a wireless (FM) receiver, a battery, electronics and display electrodes to fit in the mouth. Components are designed to be able to fit in custom retainers inside the mouth, and the electrode array displays information on the tongue. Advantages of the tongue as target for stimulation in comparison to fingertips are: better perception, a lower skin resistance (a much lower stimulation voltage will be sufficient), and the presence of saliva (acting as electrolyte, improving electrode contact)[10].

A problem that has yet to be solved is that no new method to encode information has been found that allows full use of the information processing capabilities (bandwidth) of the skin. However, multiple known encoding schemes could still be adequate for the creation of certain types of applications that would require only a fraction of the full bandwidth of the skin.

5.2 The difference between theoretical and practical bandwidth

"Since the information rate achievable via tactile displays are low, the need for optimal encoding of information into electrocutaneous stimulation is great." - Andrew Szeto, 1982 [31]

As discussed in section 3.3, the estimated (theoretical) bandwidth of the skin is orders of magnitude greater than the actual information rate currently achieved through electrocutaneous stimulation (only 2-5 bits/s per electrode). Higher bandwidth data should be communicated through multiple electrodes, possibly in combination with more efficient encoding of information into waveforms[31]. The optimal method to encode and present information through electrodes on the skin is still subject of debate, and more research is needed to establish an unambiguous answer.

A relatively high electrocutaneous information rate from a single electrode was recorded by Kokjer[7], he examined the order of magnitude of the maximum capacity of a skin channel for transfer of information, by increasing the frequency of bursts of pulses to find the point where subjects could not differentiate between pulses anymore. He found that over the data collected from 4 subjects, the values for channel capacity ranged from 2-56 bits/sec[7]. Since Werner and Mountcastle estimated the bandwidth of a single neuron transferring signals from cutaneous mechanoreceptors to be 5-10 bits/s[63], Kokjer suggests that multiple afferents are contributing, even with a very small stimulation surface[7].

Though no high-resolution tactile displays are on the market yet, the unique properties of the skin as input channel could still make it an option superior to the other common input channels, considering functional demands of some interfaces. In some applications, reaction times are very important, and the commonly used visual system is known to cause a significant delay[10][64]. Reaction times are lower when information is presented through the sense of touch in comparison to stimuli presented visually, because the retinal delay is much larger that the signal transduction delay through the touch sense in the skin[10]. The principle that the skin is better suited to faster, serial input than the visual system. is illustrated by the example that the eye can not easily discern variations in frequency above about 60 Hz, but the skin can easily perceive vibrations up to 400 Hz[9]. *"Therefore, while the skin is poorer than the eye at processing spatial information, it is superior at processing serial information"*[48]. The most important fact remains that the best sense to use as input channel can only be determined after considering the strengths and weaknesses of every potential input channel, selecting the best channel to meet the functional demands of the interface in question.

Geng states that consistency of perceived sensory input resulting from electrocutaneous stimulation is hard to guarantee because the perceived stimulus intensity is a result of stimulation parameters that influence each other, and the perceived intensity changes non-linearly with stimulus parameters[65]. These effects, in addition to the phenomena of dynamic range and sensory adaptation, give rise to a challenge that has not yet been solved adequately: how to create electrocutaneous stimuli that result in sensations that are consistently perceived to be of constant intensity?. According to Geng, a consistent magnitude of a perceived stimulus is important when electrotactile stimulation is used to provide feedback from prosthetic limbs[65]. Considering the importance of feedback loops (consisting of motor control and related sensory input) for the formation of the mental model of "reality" (as illustrated by the principle of telepresence), the acceptance of prosthetic devices will increase significantly if adequate sensory input from the device is provided: important factors to consider are the "feeling" that the "machine part" is actually part of the users body, as well as improved control over finer movements.

5.3 Impact of experimental setup on results

The author hypothesizes that the optimal approach to transferring information through the skin has not yet been recognized as being the best, or most effective method, because the published studies attempting to compare different methods did not use an experimental setup suitable to find it. Visual or auditory displays often attempt to present information in a "familiar" way: sounds are created to resemble existing sounds, graphical user interfaces use mundane geometric patterns. Those patterns are recognized after a life-long period of learning, whereas information presented to those senses in an unfamiliar way might be discarded as noise.

Experiments in the field of (electro)tactile displays are often limited by time constraints[34], leading to important problems that distort experimental results: training the brain to recognize and interpret new types of complex patterns costs more time than is commonly available for experiments involving multiple subjects. Thus, for such trials, the examined methods of displaying information have only been tested using (a repeated sequence of) simple patterns, because more complex pattern recognition has to be learned (which takes to much time). Also, limits imposed by sensory overload could be reduced after more training time. It is possible that the optimal method to encode information only looks like a viable method AFTER the brain is trained. Before training, inherently inferior methods might seem to yield superior performance! Could it be possible that methods which were discarded because of an observation they resulted in rapid sensory adaptation (in a situation where the user was bombarded with redundant low-resolution data), are actually methods that would allow the transfer of streams of more complex, higher bandwidth data? If so, the brain would first need to learn to recognize the new input patterns before it could make sense of the data. Before such training, the input signal would probable be discarded by the brain as noise, leading to poor performance during trails. This conclusion was reached based on information discussed in section 3.7.

6 Design of a transcutaneous stimulator

More research on cutaneous displays is required. They hold great potential for new man-machine interfaces, while also providing more insight into the fundamental mechanisms of brain plasticity, and the ability of the CNS to learn to interpret new "modes" of sensory input. Transcutaneous displays are a relatively low-impact approach to the exploration of these phenomena because they do not require surgery, or other invasive methods. Instead, they can be integrated into wearable devices. This fact also increases commercial potential, because products depending on invasive methods can not (easily) be made available to the general public (end-users).

In the case of the TVSS (described in more detail in section 4.1), the transcutaneous display is not used as part of a "traditional" interface. The "traditional" model of an interface (according to the Abowd and Beale framework of interaction, covered in section 2.1) assumes that the machine is merely responding to situations initiated by a user, and it also assumes that two-way communication between the user and the machine is taking place. Depending on the application, cutaneous displays could be used as a one-way information channel from a machine to a user, or as part of a "traditional" interface, possibly co-existing with more common interfacing devices (keyboards, screens and the like). An example of an electrocutaneous display as part of a "traditional" interface is shown in figure 6.1:

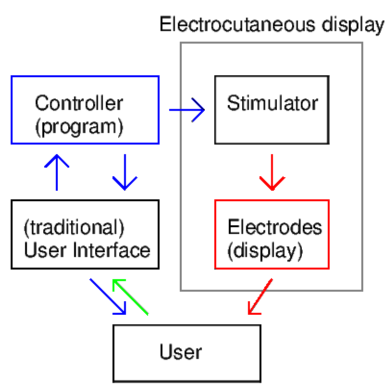


Figure 6.1: A high level overview of an interface utilizing a transcutaneous display. Red indicates stimulation current, green indicates user control, blue indicates software control.

In order to be able to design and perform experiments that rely on electrocutaneous displays, a stimulator unit is the very first requirement. However, such units are (as of this writing) not available through (common) commercial channels. As a consequence, it is not uncommon for researchers in the field of electrocutaneous stimulation to build a custom stimulator[5][66][67][68]. The process of designing a stimulator from scratch is likely to take a significant amount of effort, time and money. An additional obstacle is that designing a device suitable for electrocutaneous stimulation is a multi-disciplinary effort: it requires, at the very least, knowledge of electronics and human physiology. For these reasons, stimulators are practically out of reach for aspiring researchers and hobbyists starting out in the field, especially when they are on a limited budget. This is even more true for those interested primarily in the exploration of new interface types that make use of this technology, rather than the design of electronics. Thus, the absence of cheap off-the-shelf stimulators for experimentation is possibly turning away a significant number of researchers (and hobbyists) interested in examining the possibilities of new "types" of human input, implicated by principles such as brain plasticity (explained in section 3).

A design for a low-voltage, low-cost electrocutaneous stimulator prototype (meant for stimulation of mechanoreceptor afferents), built from common (commercially available) components, is presented herein. The stimulator requirements are defined in the next subsections. Experiments to test if the assembled stimulator prototype is able to produce perceptible sensations are presented in sections 11 (methods) and 12 (results). Improvements to the stimulator are described in section 13 and experiments to test the improved prototype are described in section 13.6. The performance of the improved stimulator is evaluated in sections 14 and 15.

6.1 Stimulator requirements

The first step towards the design of a stimulator is the specification of the stimulator requirements. Though it would seem obvious to delay the selection of components until the initial specifications are clear, in practice specifications can change as the projects matures. This is especially true in the case of "new" research (no previous experience in the field, all knowledge comes from literature). A solution to this problem is to design the stimulator in modules from the start. Any module could be replaced, if the need arises. For instance, in the case that testing proves the performance of a part to be inadequate, or if the stimulator requirements have changed as a result of practical experience.

A number of considerations result in a list of specifications. After these initial priorities are defined, a list of finer-grained specifications can be composed. Considerations defined for the stimulator design described herein are presented in table 6.1, ranked by priority.

Table 6.1: Stimulator design considerations.

Description	**Priority**	**Elaboration**
Safety	Highest	Risk of severe injury is to be minimized.
Stimulator capabilities	High	Adequate quality of stimulator output.
Cost	Medium	The budget is limited.
Uncomplicated	Low	Avoid unnecessary complexity of electronics.
Component quality	Lowest	Reliable and durable components and electrodes.

The most important consideration is safety. Electrocution can be lethal[69], but death is not the only dangerous reaction of the human body to electrical current. Stimulator safety is complicated because multiple hazards have to be avoided, some of which are easily overlooked. The issue is addressed in section 8. Most important from a research point-of-view, are the characteristics of the stimulator output signal(s). If the stimulator is not able to generate any perceptible signal, other considerations are no longer relevant. However, a stimulator does not need to be able to generate all conceivable types of output signals, or have a very high compliance voltage in order to be useful for experiments. How to determine the exact requirements of the stimulator's capabilities are explored further in section 6.2. The considerations of cost and complexity are relatively straightforward: commercially available electronics components and ICs are to be favored over complicated circuitry. In addition to the considerations listed in table 6.1, it is considered a good thing if the design for the stimulator described herein could be made available (for use and modification) to the public, aimed at researchers and hobbyists. Increasing the availability of stimulators is expected to make the field more accessible to "new" researchers, and this is expected to increase the rate of exploration of the possibilities that exist as a result of the plasticity of the human brain.

6.2 Output capabilities

The range of experiments that can be performed using a stimulator is determined by the selection of output signals the stimulator is able to produce (reliably). Though stimulator output is a complicated matter (because of the number of relevant parameters), the first priority is a perceptible output signal. Selection of components that result in a stimulator that is not able to generate a perceptible wave shape, is a waste of time and resources, but over-specification of components can lead to unnecessarily expensive or complicated designs. A stimulator does not necessarily need to be able to produce all waveshapes within the range of useful stimulation parameters as described in literature to be useful for research. As described in section 4.4, multiple feasible methods of encoding information into an output signal have been compared in literature. A number of design decisions were made regarding a prototype of a transcutaneous stimulator, they are presented in table 6.2 and motivated in the following paragraphs.

*Table 6.2: Stimulator design decisions. * Electrode types are compared in section 7.1. ** Multiple stimulator units should be used from a single control unit for multi-electrode experiments. *** Thicker skin likely requires compliance voltages higher than Vcap.*

Description	**Chosen**	**Unsupported**
Wave type	functionally monophasic	balanced biphasic
Voltage cap (hard)	30 V	30+ V
Current cap (soft)	10 mA	10+ mA
Electrode type	concentric ring	other*
Electrodes per unit	single pair	multiple **
Electrode material	grade 316 steel	
Skin locus	forearm	fingertips ***

The perceived stimulus is impacted significantly by electrode type and dimensions, as well as location on the body, pulse characteristics, and user training. This stimulator design is in fact a switched current source. In the case of the prototype, the current is controlled manually (by the user), the voltage is adjusted between 0V and Vcap in order to keep the current at a constant level. The function of the current cap is to prevent painful or dangerous currents from flowing in the case of components failure or a user mistake. If a situation occurs that would require higher currents, the current cap could be changed, and the maximum current supported by electronics components is likely higher than 10mA. The voltage cap is to prevent damage to electronic components. Without the voltage cap, the current source circuit would attempt to increase the voltage beyond the component rating whenever the resistance between electrodes becomes too high (for instance as a result of poor electrode contact or high skin resistance).

A range of electrode types suitable for cutaneous stimulation has been described in literature, a selection of electrode types is discussed in detail section 7.1. For the stimulation experiments described herein, several reasons existed for choosing concentric ring electrodes: a single pair consisting of a center electrode and a return ring electrode can be used to deliver output from a single stimulator unit, and these electrodes are likely suitable for delivering localized current pulses. However, optimal electrode dimensions are to be determined experimentally. The results of the comparison of electrodes (regarding perceived stimulus quality) is presented in section 14.3.

For the stimulator design described herein, it is assumed that displays relying on multiple electrodes can be build from separate pairs of concentric ring electrodes, all powered from separate current sources (per electrode pair). The reason for this is that the current source controls the current through the total number of electrodes connected, so if current control per electrode pair is desirable, every pair needs its own current source.

Properties of the skin relevant to electrocutaneous stimulation (factors that impact skin resistance and receptor content) change with skin type, which is determined by location on the body (as explained in section 4.2). In general, skin resistance is higher where skin is thicker. According to Ohm's law, a stimulator would require to increase the voltage to maintain the same current in comparison to stimulation of a lower resistance (thinner skin area)[70]. Skin on fingertips is relatively thick, so current pulse displays for fingertips require relatively high compliance voltages[66][71][72]. However, a high voltage stimulator has a number of disadvantages in comparison to a low voltage stimulator: assuming equal stimulation current, higher voltage results in a higher power consumption, and high voltage stimulation is more likely to cause tissue damage (burns). Dangers of electrotactile stimulation are covered in detail in section 8.

Fingertip stimulation could require a potential of hundreds of volts across the electrodes[55][66][71][72], but for locations on the body with lower skin resistance, a much lower voltage could suffice. Szeto and Saunders state that *"Comfort is maximized if the compliance voltage is limited to +/- 50 V."*[25]. Because of the (optimal) conditions in the mouth, tongue stimulation requires even less voltage (about 3 percent in comparison to fingertip stimulation) and current: 5-15 V and 0.4-2.0 mA respectively[43]. According to A. Elsenaar, a voltage of 30 V should be sufficient for transcutaneous stimulation (personal communication, April 16, 2013). The stimulator design described herein is a low-voltage one, which means a it is likely that this stimulator will not be able to deliver perceptible current pulses through fingertip skin.

When using a functionally monophasic waveform stimulation waveform, it matters for the perception of the signal whether the stimulation (from the active (center) electrode) is negative or positive (one might work better than the other in practice). However, not all skin loci react the same to stimulation of a certain polarity. For instance, stimulation of the fingertips and tongue works better with positive stimulation, but for stimulation of the skin on the forearm, negative pulses could work better[K. A. Kaczmarek (personal communication, June 28, 2013)].

Data can only be encoded into wave parameters that are software controlled. This design allows for software control of the frequency of a square wave, and its duty cycle, but not over amplitude (current). The stimulation current is controlled manually by the user because this allows the user to increase the stimulation current to compensate for adaptation, or decrease it in the case of painful sensations. The usefulness of a higher resolution of control over frequency and duty cycle goes down when the step size becomes much smaller than the minimal perceptible difference (see section 4.4 for more information on the encoding of data into wave characteristics).

Szeto and Lyman compared several schemes to encode data[34]. They made a number of recommendations regarding the effectiveness of stimulation waveshapes:

1) Encoding schemes relying on the modulation of frequency are more comfortable than those modulating amplitude (current).
2) Sensory adaptation is minimized by using low frequency monophasic stimulation pulses.
3) The most effective single electrode code examined in the study was Low Pulse

Rate Modulation (data encoded in pulse rates from 1 to 15 pulses/second).
4) Encoding of data into signals across multiple electrodes improves performance.

An overview of sensible waveform characteristics suitable for electrotactile stimulation has been published by Kaczmarek et al.[55]. Starting values for stimulation wave characteristics were obtained by combination of this data[55] with Szeto and Lyman's recommendations[34]. Data should be encoded in frequency and/or pulse width. Stimulation frequencies most useful for stimulation are likely in the range of 1 to 100 Hz. Such frequencies are not close to the limitations of hardware (regarding PWM frequency). Therefore, the stimulation frequency can be increased in software for experimental purposes (even beyond the "useful" range). Experimentation with pulse duration (pulse width) might be worthwhile too, values from literature[55] were used as starting point.

An overview of specifications for the output signal of the stimulator is presented in table 6.3:

Table 6.3: Stimulator output capabilities.

Parameter	**Supported range**	**Control**
Current	0-10 mA	manual (user)
Voltage	0-30 V	automatic (current source)
Wave frequency	0-1000 Hz	automatic (software)
Pulse length	2-1000 (step 0.2) μs	automatic (software)

6.3 A high-level overview of a stimulator

Electrocutaneous displays rely on the principle of communicating information to the brain, through the stimulation of afferents with electric pulses (data is encoded into wave shape parameters). An electric stimulation pulse is a flow of current (electrons) from one electrode (anode), through the skin, to another (cathode), triggering the firing of neurons associated with mechanoreceptors in the skin in the process. Several high-level components make up an electrocutaneous stimulator: they are often functionally similar across designs[5][66][67][68]. An overview of the components is presented in figure 6.2.

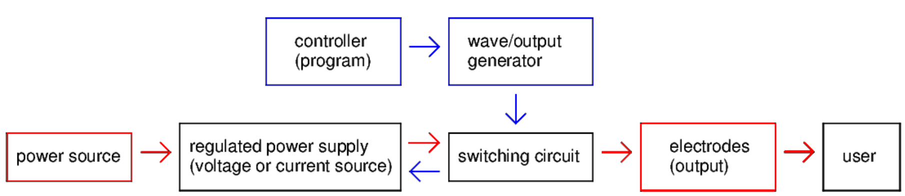


Figure 6.2: A high level overview an electrocutaneous stimulator. Red indicates stimulation current, blue indicates software control.

The regulated power supply produces a controlled electric output signal (commonly of constant voltage or constant current) from a power source. A controller encodes information into a wave shape according to a program (software), and it affects the output signal accordingly, through the switching circuits. In the case of the stimulator described herein, information can be encoded in wave frequency and duty cycle (pulse duration), so the switching circuit (controlled by software) only needs to form/break a conducting path from the regulated supply (current source) to the electrodes to generate the output wave. If software control over current is required, an additional interface (switching circuits) between the controller and regulated power supply is required: this is represented by the arrow from the switching circuit to the regulated power supply in figure 6.2).

As mentioned in the sections about stimulator requirements and output capabilities (sections 6.1 and 6.2), the requirements for a stimulator depend on many factors specific to a certain application (research, medical, entertainment, or otherwise). Therefore, this stimulator was designed in a modular fashion. For instance, the regulator module might accept power from a range of power sources, as long as the voltage range is within bounds specific to the regulator module. The same goes for the control unit: its output signal could connect the regulator and electrodes through any switching circuit (as long as voltage and current ratings of components are considered, obviously), and the reverse is also true (controller units can be made interchangeable). The design and testing of the modules making up a stimulator is covered in sections 9 and 10 respectively.

7 Electrodes

Electrodes form the interface between the stimuli (electric pulses) generated by the transcutaneous stimulator, and the user. The type, shape, size, and material of the electrodes can impact the perceived stimulus significantly. Electrode material has to be chosen carefully, materials like iron or copper are prone to electrochemical (redox) reactions under stimulation conditions. Electrode shape impacts the distribution of current (see section 4.3), which determines which neurons in the skin will be stimulated (most).

It is important to note that while the electrode type and size might increase or decrease the dynamic range of the stimulation, the electrode type is likely unimportant for examining the underlying mechanisms of brain plasticity. If the brain has learned to interpret patterns of input received through afferents in the skin, it does not matter whether they are stimulated transcutaneously or subcutaneously.

7.1 Electrode types

Invasive methods allow for implantable electrode types, but the prototype described herein assumes transcutaneous stimulation (electrodes are placed on the skin) for reasons of practicality. The disadvantage of surface electrodes is that the stimulation of efferents through the skin requires a high voltage, in comparison to stimulation from under the skin. An overview of electrode types is presented in table 7.1.

Table 7.1: Electrode types.

Electrode type	**Location**	**Characteristics**
Fine wire	Subcutaneous	Wire inserted through the skin [4][36]
Cuff electrode	Subcutaneous	Wrapped around a nerve [36][68][74]
Disk electrode	Subcutaneous	Implanted [4]
Coiled wire	Interneural	Inserted into a nerve for recording purposes [36]
Microelectrode	Interneural	Array of 25-100 electrodes, shot into nerve bundles [36][74]
Two electrodes	Surface	Two separate electrodes [73]
Concentric rings	Surface	Two rings, coaxial [55]
Line electrodes	Surface	A finger is placed on, or moved over strips of metal [46][47]
Array	Surface	Array of active electrodes, single (large) return [61]
Array	Surface	Polarity switching electrodes [44][35]
Array	Surface	Adjustable weighed return path [73]

A stimulation circuit requires a user to be connected to at least two electrodes. The simplest design requires two electrodes, with the current flowing in a fixed direction. Kajimoto et al. used strips of metal as electrodes (a finger was moved over the strips)[46][47]. Concentric ring electrodes consist of a center electrode, surrounded by a return electrode (with a larger surface area), separated by an air gap. The concentric electrode design leads to a localized current flow, (from the center to the return electrode) decreasing the current flow outside the electrodes[55].

A design for a stimulator array has been described where (a grid of) active electrodes were placed like "islands" (separated by an air gap) in a large common return electrode[61].

It is possible to change the functions (anode, cathode, or disconnected) of electrodes in an array in real-time: single electrodes could be activated sequentially, while the remaining electrodes act as the return. This approach was used for the forehead display described by Kajimoto et al.[35]. A variation on this approach has been used for an electrode array placed on the tongue[44]: a square array of 12x12 electrodes was divided in 4 square groups of 6x6 electrodes. One electrode is activated at a time in each group, while the remaining electrodes act as the return. It was noted that current distribution is expected to be different for edge electrodes because they are not surrounded by electrodes like the ones in the middle are[44].

In more complex designs, the distribution of current could be controlled by manipulation of a complex return path (by activating patterns of return electrodes, possibly with weighted paths). If the connections to, and polarities of, the electrodes in an array can be switched, a stimulation system can achieve greater control over the distribution of current in, and under the skin[73].

7.2 Electrode materials

The choice of electrode material is not only important for reasons of price and durability, but materials that are prone to electrochemcial reactions that might occur at the electrode-skin interface during stimulation, are to be avoided. This is especially true for subcutaneous (implanted) electrodes[73].

Single electrodes have been produced from a range of materials, including carbon rubber (high resistance, chemically stable), hydrogel (layers of conducting gel on a metal or carbon substrate), metal plates covered by fabric (fabric is soaked in electrolyte solution)[73]. Smaller electrodes, concentric ring electrodes, and electrode arrays are commonly produced from various metals[4][55]. Electrode textiles have also been described[73]: wire is woven into the fabric tissue to form conductive pads. According to Szeto and Saunders, acceptable electrode materials should not develop a non-conductive surface area when conducting electricity through tissue[25]. Materials noted in literature include gold (plated), silver, platinum, platinum/iridium, titanium, and stainless steel[4][17][25][36].

A notable example is the tongue display unit, which consists of an array of 12x12 gold plated copper contacts on a flexible insulated strip, produced by a commercial flexible printed circuit vendor[44].

Electrolyte gel improves the contact between the skin and the electrode surface[73], but if the conducting layer is too thick and the gel resistance too low, short circuits are likely to occur.

For the first stimulator prototype tests, optimal electrode materials were unavailable. Therefore, a concentric ring electrode pair was made from iron to be able to test if the stimulator design actually worked. The procedure for testing the prototype is described in section 11. However, such electrodes are far from ideal (they are prone to redox reactions), they should be avoided if better materials are available.

Subsequential testing of the stimulator described herein was done with steel concentric ring electrodes described in section 13.1. Stainless steel (grade 316) was used as the electrode material of choice because of its relatively low price in comparison to titanium or gold, and high availability. However, copper wires can not be soldered directly to the 316 steel using the same methods commonly used for soldering electronics components (standard soldering iron, flux and solder). A solution to this problem is presented in section 13.1.

7.3 Electrode size

The distribution of current is affected significantly by irregularities in the both the skin and the electrode[73]. Additionally, if the electrode surface is only partially making contact with the skin, current distribution changes radically (current distribution peaks)[25][73]. Szeto and Saunders illustrate this principle: *"If a 12 mm^2 electrode is tipped on its edge, its current density rises about 10-fold, and the sensation becomes prickly and uncomfortable."*[25]. Current densities are higher around the edges of electrodes[25][73]. Electrode size impacts the stimulus intensity (and occurrence of pain). Generally, a small electrode reduces stimulation comfort, because of a larger current density[73]. An electrode that is too small is likely to cause painful stimuli, thus reducing the dynamic range[4][62]. However, smaller electrodes allow for greater stimulation selectivity (especially when activating muscles)[73].

According to Keller and Kuhn, optimal pad electrode size for transcutaneous electrical stimulation is 0.8 x 0.8 cm (64 mm^2)[73], but according to Szeto and Saunders, the size of the active electrode should not exceed 15 mm^2 because of the increased chance of skin inhomogeneities that could result in current collapse[25]. As a guideline, they suggest to limit the current amplitude to 1mA/mm[sic][25]. Kaczmarek and Bach-y-Rita state that a high chance of current collapse as a result of a large electrode surface would occur with surfaces over 100 mm^2[4].

Common diameters for center and return electrodes (concentric ring type) are reported to be 2-10 mm (3-79 mm^2) and 4-100 mm respectively, separated by a 1-4 mm air gap[55].

The available surface of usable skin limits the number of electrodes in a tactile display. Kajimoto et al. used electrodes with a diameter of 2.0 mm (3.1 mm^2, spacing (center-to-center) of 3.0 mm), for their 512 electrode forehead display[35].

A fingertip-scanned array of 7x7 electrodes (round stainless steel, diameter of 0.89 mm (0.62 mm^2, spacing (center-to-center) of 2.54 mm, with a 2.36 diameter air gap) sharing a common return has been described[61], which has also been used for stimulation of the tongue[43]. Ostrom et al. described a microfabricated array of comparable layout, with center electrodes of 0.8 mm

(0.5 mm^2, spacing (center-to-center) of 2.4 mm)[75]. A tongue display unit with 12x12 1.55 mm diameter (1.89 mm^2) electrodes was described more recently[44].

8 Safety

Electricity can be a serious hazard under certain conditions. Various of physiological effects are known to occur when (a part of) the human body becomes part of an electrical circuit. Electrotactile stimulation relies on one of those physiological effects (to trigger a neural action potential), thus the subject has to become part of a circuit. This means extra care has to be taken to avoid the conditions that can result in a situation where the electrical current causes tissue damage, or death. Electric current is known to results in a number of physiological phenomena (examples are given of effects resulting from low and high currents respectively) [69][87]:

1) Sensory reactions (perception, pain)
2) Muscle reactions (twitch, tetanic contractions)
3) Resistive heating of tissue (reversible, tissue damage)
4) Electroporation (reversible, tissue damage)

Figure 8.1 shows an overview of physiological effects occurring at increasing electrical current. The image in figure 8.1 was taken from the chapter on electrical safety by W.H. Olsen, in the book Medical Instrumentation: Application and design (1987)[69]. Effects are based on 60 Hz (alternating) current via the hands (through copper wires) of a 70 Kg human, for 1-3 seconds[69]. Note that thresholds are expected to be lower for DC current in comparison to AC current[87]. The perception thresholds for DC current decreases also if DC current pulses are applied[87].

A current pulse should be above the threshold of perception to be useful for electrotactile stimulation. A stimulator capable of delivering current pulses in the range of 0 mA to 50 mA should be able to replicate the current of any experiment mentioned in literature[55], but stimulation currents between 0.5 mA and 10 mA are likely to be sufficient (especially if data is not encoded in amplitude), such currents have been used for experiments described in literature[25]. The mean thresholds of perception (AC current) are estimated at 1.1 mA and 0.7 mA for men and women respectively[69].

The let-go current is the point where muscle tissue is stimulated to the point the human can not voluntarily ”let go” (stretch fingers) anymore. Increasingly strong continuous muscle stimulation might result in fatigue, pain, tissue damage, and respiratory paralysis. Higher currents can result in sustained contraction of the heart muscle[69][87].

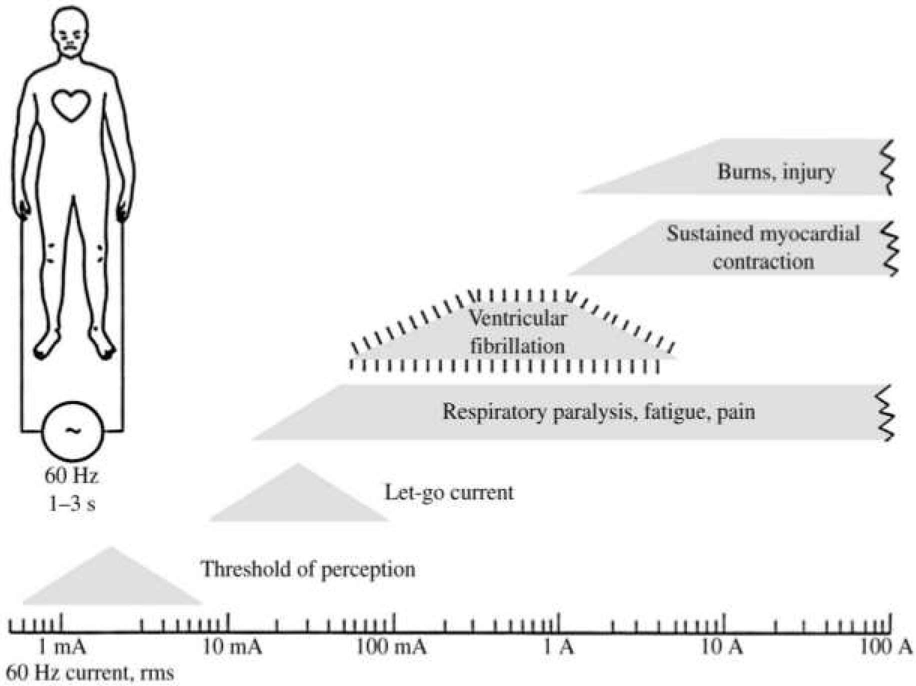


Figure 8.1: Physiological effects of electricity, taken from the electrical safety chapter (W.H. Olsen,1978)[69]

Damage at the electrode/skin contact area can be the result of resistive heating, or electrochemical reactions. With a higher skin resistance, the voltage required to produce a constant current pulse increases (according to Ohm's law: I=V/R[70]). Assuming a constant current, electrical power is increased with voltage (power=current*voltage), this increase in power translates to an increase in heat (this is resistive heating). Large thermal burns are unlikely to occur under common stimulation conditions[17].

Electrochemical burns are a result of redox reactions caused by the potential gradient created by a stimulator pulse[73]. Dangerous reactions are stated to be the electrolysis of water, metal dissolution, and saline oxidation[25]. Biphasic pulses are less likely to cause irreversible chemical reactions, as every voltage gradient is followed immediately by a negative voltage gradient of equal magnitude[17][25]. The problem of electrochemical reactions as a result of DC stimulation is reduced significantly if the electrode output is capacitively coupled (zero-dc)[25]. This is achieved by placing a capacitor over the output electrodes, the effect is that the voltage during the "low phase" of the square wave is lower than 0V, the "area under the curve" (charge) of the "high phase" and "low phase" are equal. This principle is illustrated in figure 4.8.

Higher current densities may lead to (sudden) painful stinging sensations (as described in detail in section 4.3), possibly causing black marks (0.25 mm diameter) on the skin[17].

An overview of problems resulting from electrical current is presented in table 8.1:

Table 8.1: Physiological effects of electrical current.

Current	**Location**	**Short term effect**	**Long term effect**
High	Heart	Fatigue, pain, death	Tissue damage, death
High, continuous	Muscle/efferent	Pain, muscle cramp	Muscle/nerve damage
Medium, low frequency	Muscle/efferent	Unpredictable	Nerve/tissue damage
Medium	Electrode/skin area	Stinging pain	Skin redness (reversible)
Any, lengthy stimulation	Electrode/skin area	-	Skin redness (reversible)
High-voltage pulses	Electrode/skin area	Pain	Thermal burns
DC pulses/High-voltage	Electrode/skin area	Pain	Electrochemical damage
Low	Through heart	Cardiac fibrillation	Death

Only currents of magnitude "medium" or lower are used for electrotactile stimulation, but in the case of component failure, higher currents may flow through the user, depending on the stimulator design.

Post-stimulation skin redness fades away over time, it is not considered dangerous. Redness increases with stimulation current, both for biphasic and monophasic waveforms. Because monophasic stimuli require smaller current amplitudes than biphasic stimulation (to produce stimuli that are perceived equally strong), they cause less post-stimulation redness in practice[25]. The disadvantage of using monophasic pulses (in comparison to biphasic ones) is the occurrence of redox reactions, this is true even for capacitively coupled pulses (although to a lesser extent)[25].

The combination of a low stimulation frequency with pulses of a relatively high current could result in nerve damage[A. Elsenaar (personal communication 17-6-2013)]: this is even true for currents that would be considered safe to use for muscle stimulation under normal (pulse train) conditions!. Sudden high currents can cause extreme muscle contractions (to the point of muscle damage and destruction of tendons)[76].
A summary of safety guidelines for stimulator design:

1) Only the physiological effects occurring at relatively low electrical currents are useful for electrotactile stimulation, physiological effects from relatively high electrical currents are dangerous, and to be avoided.
2) Current pulses of high voltages can lead to thermal burns. Aim for lower skin resistances to reduce the voltage required for a perceptible current pulse.
3) Powering the device from low-voltage DC reduces the risk of electrocution in the case of component failure.
4) Biphasic and zero-DC (functionally monophasic) stimulation cause less electrochemical reactions than monophasic stimulation.
5) Don't combine a low pulse frequency with pulses of relatively high current.
6) For muscle stimulation, modulate a continuous 50Hz wave.

9 Module design - methods

This section covers the modules that make up the design of a prototype for a electrocutaneous stimulator. The goal is to design modules that result in a stimulator that meets the requirements listed in sections 6.1 and 6.2. The specification of requirements resulted in additional design decisions:

1) All modules (regulator as well as the controller) are to be powered from batteries (low-voltage DC, preferably in the 2.5-5V range), not from mains power.
2) The regulated power supply is to supply a (manually adjustable) constant current.
3) The switching circuit is to be able to transfer the output wave shape to the electrodes unmolested (without modifying it significantly).
4) Electrode output should be functionally monophasic, but zero-dc (capacitively coupled).

Note that requirement (3) will not be met if the output of the regulated power supply can not be switched fast enough, as a result of properties of the regulated power supply.

9.1 A regulated power supply

Because the resistance of the skin changes with current, a stimulator providing current pulses is preferable over voltage pulses (see section 4.3). The power supply should fail safely (it should not cause any permanent damage to the user): sometimes components fail, this has to be considered in the design of the module. A low-voltage battery supplying the power supply would be inherently safer than powering the stimulator from mains voltage, because component failure could never result in a situation where electrodes (connected to a user) would be exposed directly to mains voltage. Low-voltage devices can be considered inherently safer than high-voltage ones[17][69][73][87]. In order to use the stimulator together with common portable devices (like laptops, smartphones, or other standalone portable devices), a portable power supply would also be more practical.

The power supply (power source and regulated supply) should be able to handle the rapid on- and off-switching required by the wave generator (controller output). It should react sufficiently fast, and with minimal overshoot. Consider a current source that reacts to slowly: if the wave generator blocks current from flowing (the "low" phase of the wave), the current source will increase output voltage to its maximum in order to maintain a constant current (which it can't, because the resistance is very high). When the wave generator switches to the "high" phase, the resistance across the power supply output suddenly drops to the resistance of the electrode-skin interface, and if the power supply reacts to slowly, the potential over the electrodes would be highest voltage the power supply could deliver until the power supply catches up.

To keep the design uncomplicated, commercially available integrated circuits (ICs) capable of regulating voltage and current were examined. The LT1618 buck/boost converter by Linear Technology[77] was selected for two important reasons:

1) This IC is able to convert an input voltage in the range of 1.6V to 18V to any voltage in the range of 0V to 35V.
2) The IC can be made to act as either a current source, or a voltage source.

The ability of the LT1618 to regulate an input voltage up as well as down makes it suitable for use in a modular design. Its maximum output voltage of 35V is higher than the 30V defined in the specifications (table 6.2). However, the IC requires a number of components to configure its output modes, complicating circuit design (especially if the IC is to be used as a current source for every electrode pair). The LM134 series of current source ICs (also by Linear Technology)[78] has fewer functions in comparison to the LT1618, therefore it requires a less complicated circuit to regulate its output current. A disadvantage is the fact that it is only able to decrease its input voltage (from the power source module), and its maximum voltage is 30V: barely adequate to satisfy the requirement of 30V. The LM334 IC was selected because of its convenient package (3-lead plastic) and availability. If the LM334 is used as a current source (per electrode pair), the LT1618 would still be a useful IC to increase the voltage from batteries to the 30V required by the current source, the LT1618 would be part of the power source module. If the LM334 can't be used as a current source, the LT1618 could be used as regulated power supply module instead.

Performance evaluations of the modules based on the LT1618 and LM334 ICs are presented in section 10.2. A photo of the experimental circuit for testing current sources is shown in P2, in the appendix.

9.2 Controller - wave generator

The controller generates pulses on its output pins. Software on the controller determines the desired wave characteristics (encoding of data into wave parameters also happens here). Subsequently, the wave shape is converted to a train of current pulses through the electrodes (user) via the switching circuit. In practice, the controller requires a programmable chip capable of generating PWM (pulse-width modulation, square waves) output pins (for a more details on PWM refer to[79]), as well as simple software (including a traditional user interface) for testing the performance of the other modules and components.

For the prototype, a Raspberry Pi[80] (board with Broadcom ARM SoC) running Raspbian Linux[81] was used, because of its price-to-features ratio. Notable advantages of a Raspberry Pi running a Debian-based linux system are ease of use, readily accessible GPIO pins for connection to the switching circuits, and support for hardware as well as software PWM. Additionally, the ethernet interface on the board allows for an out-of-the-box command line interface over

SSH, which provides sufficient access for all testing purposes. The device can be powered from the USB port (5V) of a laptop acting as a terminal during testing. The testing software was written in Python because of the availability of libraries to control the PWM capabilities of the Broadcom chip. The performance of the controller (output signal) is presented in section 10.1.

For testing purposes, a controller based on the Raspberry Pi worked well, but in theory, any other chip that provides programmable PWM output and a way to send commands and data to the device (like a serial connection) would suffice. For instance, a controller based on a Microchip PIC would be cheaper and smaller than a Raspberry Pi, and consume less power.

9.3 Switching circuit

Switching circuits act as interfaces between the controller module, regulated power supply module, and electrodes. In the case of the design described here, the switching circuit switches the voltage on the electrodes (from the regulated supply) on and off, according to the output signal of the controller module. If software control over current is required, this can be achieved through a switching circuit between the controller module and the regulated power supply.

Optimally, all modules are powered from batteries. In reality, the controller module might be connected to mains directly or indirectly (connected to a mains-powered machine via ethernet or USB). The circuit from the power source to the electrodes connected to the user and the controller module and its power supply should be optically isolated. This protects the power supply-electrode circuit (the user) from mains power, and it protects the controller from current pulses from the power-supply-electrode, in the case of (unexpected) component failure. Therefore, the switching circuit will rely on optocouplers (LED-phototransistor pairs) to enable galvanically isolated communication between the two circuits. A circuit for testing a switching circuit is presented in S3 (in the appendix), a photo of a switching module is shown in P1 (in the appendix).

Selecting the optimal optocoupler is complicated by the fact that although a large selection of different optocouplers is commercially available, optocoupler characteristics are often not listed in stores, and the only way to evaluate their capabilities is by reading the data sheet for every single device. Several optocouplers were examined, their respective performances are presented in section 10.1. Important characteristics to consider when selecting components[70] are switching speed, maximum switching voltage, maximum switching current, and as it turns out, in some cases resistance is also a significant factor, as illustrated in section 10.2.6.

9.4 Software

The function of the testing software is to generate output waves in order to examine the performance of the controller module (the quality of the PWM signal), and the switching circuit. It is important to verify the controller module is generating the output signal as expected, and that the switching circuit is not changing its characteristics significantly. The testing software consists of a series of Python scripts (running on the controller module, controlled over SSH from a laptop) that generate PWM output of various frequencies and duty cycles continuously, for module performance evaluation. For testing if the stimulator prototype is able to produce perceptible stimuli, a program was included to output either a short burst, or continuous train of current pulses, in reaction to keys pressed by the test subject.

10 Module design - performance evaluation

For every module, the performance of the (previously selected) components was evaluated. Some modules depend on other modules. This problem was solved by testing the switching circuit after testing the controller and regulated power supply separately, and in some cases, by stub circuits. The testing of the switching circuit components requires a functioning wave generator, and the controller requires software to output a wave. The testing software described in the previous section was used for all module testing. Performance per module is presented in the following subsections.

The quality of the output signal generated by the testing software running on the controller was inspected visually using Voltcraft oscilloscopes (VDO-2052 and VC 630-2) connected to the PWM output pins (Raspberry Pi general purpose input/output(GPIO) pins used as such, see S2 in the appendix). For the generation of PWM output (frequencies 1Hz-10KHz, duty cycle 1%-100%), the SoftPWM functions from the Python library RPi.GPIO[82] were used.

10.1 Switching circuit

The switching circuit consists of a transistor that switches an optocoupler. After the output quality of the controller module was verified, it was used as input for the switching circuit. Criteria for performance evaluation of the switching circuit:

1) The transistor should switch rapidly enough not to modify the signal from the controller.
2) The optocoupler should switch rapidly enough not to distort the signal from the transistor.
3) The optocoupler should be able to take the current and voltage required to switch the regulated power supply.
4) The optocoupler should be able to switch the regulated power supply, without impacting the voltage/current from the supply significantly.

To verify if the components satisfy criteria (1) and (2), the quality of the output signals after the transistor and optocoupler components were inspected visually with an oscilloscope connected over the component output pins, results are presented in table 10.1.

Testing conditions: VOLTCRAFT Analog Oscilloscope 630-2, auto trigger mode, TIME/DIV=0.5ms (50ms total, 100Hz pulse=10), 100 Hz soft PWM, duty cycle 50%-70%. Raspberry Pi powered via laptop USB, laptop not connected to power. Optocoupler type: 4N33, output circuit: a red LED (for visual cues) in series with a 680Ω resistor, powered from 5V.

Table 10.1: Output wave performance evaluations.

Measuring locations	Wave shape	PWM frequency	As expected
Ras.Pi gnd/3v3 power	line	100 Hz	yes
Ras.Pi gnd/5v power	line	100 Hz	yes
Ras.Pi pin2/gnd	square, 70/30	100 Hz	yes
Ras.Pi pin2/gnd	square, 50/50	100 Hz	yes
Ras.Pi pin2/gnd	square, 50/50	1 KHz	yes
Ras.Pi pin2/gnd	somewhat distorted, 50/50	10 KHz	yes
transistor	square, 70/30	100 Hz	yes
transistor	square, 50/50	100 Hz	yes
transistor	square, 50/50	1 KHz	yes
transistor	somewhat distorted, 50/50	10 KHz	yes
4N33 output	distorted severely, 70/30	100 Hz	no
4N33 output	distorted severely, 50/50	100 Hz	no
4N33 output	distorted severely, 20/80	100 Hz	yes

From the results presented in table 10.1, a number of conclusions can be reached:

1) The tested software PWM is able to generate 1000 Hz square waves, but 10 Khz waves can not be generated reliably using these methods.
2) The transistor (C547B) is behaving as expected.
3) The 4N33 optocoupler is not switching fast enough.

After more experimentation, it was determined that under the testing conditions, the optocoupler (4N33) was switching significantly slower than could be expected from the data sheet[83]. The 6N137 optocoupler was selected because of its switching speed, but discarded because of its low compliance voltage. The voltage the 4N25 could switch (Vceo =70V) was sufficient[84]. Reported switching speed[84] was relatively low in comparison to the 6N137 switching speed[85], but it proved adequate according to the results presented in table 10.2. Therefore, the 4N25 was used as the optocoupler in the switching circuit module.

Testing conditions: VOLTCRAFT Analog Oscilloscope 630-2, auto trigger mode, TIME/DIV=0.5ms (50ms total, 100Hz pulse=10), 100 Hz soft PWM, duty cycle 50%-70%. Raspberry Pi powered via laptop USB, laptop not connected to power. Optocoupler type: 4N25, output circuit: a red LED (for visual cues) in series with a 680Ω resistor, powered from 5V.

Table 10.2: 4N25 output performance measurements.

Wave shape	PWM frequency	as expected
square, 50/50	100 Hz	yes
square, 50/50	1 KHz	yes
somewhat distorted, 50/50	10 KHz	yes

10.2 A regulated power supply

As mentioned previously, the LT1618 IC can be used either as a voltage source, or as a current source. The following subsections each describe the performance evaluation of a different module built around an LT1618 or LM344 IC, or a combination of both.

10.2.1 LT1618 voltage source

Regardless of the module type the LT1618 would be part of, its ability to regulate voltage is of vital importance. To test the voltage regulation qualities of the LT1618, a testing circuit was built (see schematics S4 in the appendix). The circuit was powered from two non-rechargeable AA batteries (2 * 1.5 V = 3V). The output voltage of the LT1618 was controlled through the selection of values of the resistors forming a voltage divider[70] (R1 and R2 in schematics S4). The voltage over the output pins connected to a 10KΩ resistor was measured with a multimeter. The initial tests showed the LT1618 circuit powered from two AA batteries (real voltage 3.04V) successfully delivered output voltages from 0V-30V.

10.2.2 LT1618 current source

The measurements described in this section (voltage, current, resistance) were all obtained using a multimeter.

The previous LT1618 circuit required no real modification in order to use it as a current source. The LT1618 output current is controlled through a resistor value (Rset). The experiments were performed with Rset values of about 5Ω and 10Ω. The expected current is calculated using the following method: for a 12Ω Rset value, the expected current is Iset=0.0677/12 = 5.6mA. The real value of the testing resistor was determined to be 12.8Ω, resulting in an expected current of Iset=0.0677/12.8 = 5.29 mA. The current through a single red LED was 5.58mA, with a voltage over the LED of 1.95V. Differences between measured current and expected current are likely due to measurement errors, both in resistance and in current.

A number of tests was performed to examine the behavior of the LT1618 as a current source, when the voltage cap was reached. The output voltage of the LT1618 was capped at 10V, the circuit was expected to output a current of 0.0677/12.7=5.33mA, based on Rset=12.7. Current through LEDs (the number of LEDs was increased from one to six LEDs) was measured using a multimeter, and inspected visually. The voltage over the individual LED(s) was also measured.

As expected, the current through all LEDs was close to 5.33 mA for 1 to 4 LEDs in series (the voltage over the series of LEDs was increased to keep the voltage over individual LEDs constant). Adding more LEDs in series caused the voltage to reach the cap of 10V (real voltage: 9.7V) for this test, and the current through the LEDs dropped accordingly. All results indicate the current source based on the LT1618 performs adequately (under the conditions of the tests). Effectively, if the voltage cap is reached, the LT1618 acts as a voltage source.

As described in section 9.1, the LT1618 is able to cope with a range of input voltages. This was verified (a single red LED, expected current 5.33 mA), measurements are presented in table 10.3.

Table 10.3: LT1618 current source: effects of input voltage.

Power source	**V(in)**	**Output current**	**Voltage over LED**
2 AA batteries	3.04 V	5.43 mA	1.95 V
ATX power supply +5V	5.13 V	5.78 mA	1.96 V
ATX power supply +12V	11.37 V	5.85 mA	1.96 V

10.2.3 LT1618 regulated current source

The LT1618 is able to decrease its output current based on the voltage over a specific pin (pin 4, see S1, S4, S5 and S8 in the appendix for examples). This functionality can be used to switch the LT1618 output (a switching circuit would be connected to this pin), or to adjust the output current from 0 up to a specified cap, by means of a voltage divider to control the voltage over pin 4[70]. The current source was connected to a single red LED. Experiments were also performed with a circuit including a potmeter as part of the voltage divider, in order to control the output current manually. The output current was verified with a multimeter, as well as visually. The experiments proved that the output current of the LT1618 could be controlled this way manually, between 0 mA and the current cap specified by the value for Rset.

10.2.4 LT1618 switched current source

The output of the switching circuit module was connected to a voltage divider on pin 4 of the LT1618 (see S5 in the appendix), in order to switch the current source on and off according to the output of the controller module (connected to the input of the switching circuit, as described in section 10.1). All results turned out as expected, this proved the LT1618 IC to be suitable for use in the assembled stimulator prototype, either as switched current source, or as power source for a different current source module. However, the LT1618 requires a relatively complicated circuit of supporting parts, especially in comparison to the LM334 current source IC. A multi-electrode stimulator would only require one power source module, but it would need one current source module for every electrode pair.

10.2.5 LM334 current source

The LM334Z current source IC (as discussed in section 9.1) comes in a 3-pin package. The pins are connected according to the schematics in S6 (appendix). Testing conditions: the current source was powered from two AA batteries (3.4

V), a single red LED was used as load. The value for Rset (for a 5mA current) was determined as follows: Iset = 0.005A = 0.0677 V / Rset. Rset = 0.0677/0.005 = 13.54Ω. Results are presented in table 10.4.

Table 10.4: LM334Z as a current source: measurements.

Measured Rset	**Expected current**	**Measured current**	**Voltage over LED**
12.7Ω	5.44 mA	5.70 mA	2.03 V
24.7Ω	2.74 mA	2.84 mA	1.93 V
98.6Ω	0.69 mA	0.70 mA	1.83 V

10.2.6 LM334 switched current source

The switching circuit output (optocoupler) could only be connected to the current set pin, because connection to other pins would disrupt power to the LM334Z, and consequently, disrupt the current regulation. The switching circuit and controller module were connected as described in section 10.1, also shown in the schematics (S7, appendix). The LM334Z was powered by an LT1618 acting as voltage source (6.7V), the Rset value for controlling the LM334Z was 12.7Ω (corresponding to an expected value of 5.44 mA), with a resistor of 390Ω as load. To examine the LM334Z performance, the voltage over the load was inspected visually with an oscilloscope. The peak voltage (pulse high phase) was expected to be around 2 V (0.390 KΩ * 5.44 mA = 2.12V). Results (as presented in table 10.5) indicate the LM334Z switching speed is not resulting in a bottleneck, but the output current was consistently much lower than expected, by a factor 10.

Table 10.5: the LM334Z as a switched current source: measurements. Duty cycle=50% .

PWM Frequency	**Shape: rise/fall/consistency**	**V expected**	**V measured**
10 Hz	ok/ok/perfect	2.12	+/- 200 mv
100 Hz	ok/ok/good	2.12	+/- 200 mv
1 KHz	ok/ok/acceptable	2.12	+/- 200 mv
10 KHz	ok/lags/poor	2.12	+/- 200 mv

Apparently, the optocoupler adds 100-150Ω of resistance to Rset. This means the maximum current the LM334Z would output, when connected to this switching module, becomes unacceptably low. The voltage over Rset is too low (0.064V) to use a transistor for switching (which requires about 0.7 V, like a diode), the obvious solution would be to use a different type of optocoupler. At this point, it was decided the LM334Z was unsuitable for use in the regulated supply module. Because the LT1618 current source performed as expected (the impact of the optocoupler resistance on the voltage divider used for control is insignificant), a proof-of-concept stimulator could be assembled from all working modules.

11 Proof-of-concept - methods

The working stimulator modules were assembled into the stimulator prototype described in the following sections. The prototype had to be tested to verify its ability to produce the expected output wave, and to prove that it is capable of producing perceivable stimuli. The experimental setup to verify these basic properties are meant to produce stimulator output that is easy to perceive, software and electrodes are not optimized for efficient data transfer. The following sections cover a high-level overview of the stimulator prototype used for testing, with a description of electrodes, a protocol for the preparation of the skin, and the setup of the proof-of-concept experiments. The results are discussed in section 12.

11.1 The stimulator prototype

A high-level overview of the stimulator prototype is shown in figure 11.1, The complete schematics for the first stimulator prototype can be found in S8, in the appendix. A photo of the assembled prototype is presented in P6 (appendix).

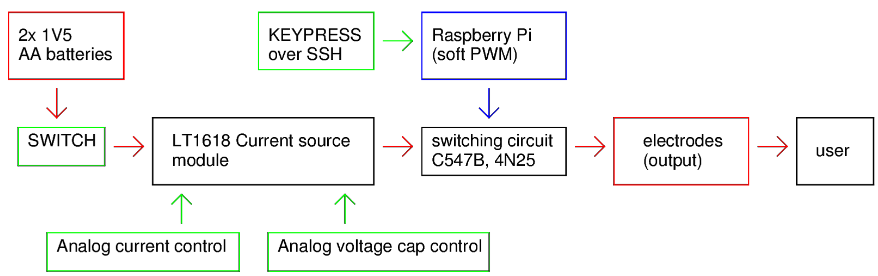


Figure 11.1: A high level overview the stimulator prototype. Red indicates stimulation current, green indicates user control, blue indicates software control.

The forearm was selected as the stimulation locus. However, it is known that properties of the forearm skin are not constant for every location. For instance, dorsal forearm skin is thicker than volar forearm skin[65]. Additionally, some locations on the forearm (for instance the wrists) have efferents close to the surface, and stimulation of those area could lead to muscle contractions. As described in section 8 (safety), low frequency stimulation waves should not be used to stimulate muscles. According to A. Elsenaar, the best (and safest) way to stimulate muscles is to use a modulated 50 Hz pulse train (personal communication, April 17, 2013). For the first tests of the prototype (and first experience with a sensation caused by electrotactile stimulation), results are unpredictable. For safety reasons (in case efferents in the lower arm are accidentally activated), a 50 Hz train of pulses was used for the first stimulation (and a frequency of 50 Hz is not unsuitable for electrotactile stimulation[34]). The pulse duration was chosen to be very long (10 ms), to increase the intensity of the sensation.

11.2 Proof-of-concept electrodes

Small electrodes are more likely to produce perceivable (possibly painful) stimuli, because they cause a greater current density (this is explained in section 7.3). The size of the proof-of-concept electrodes was based on the dimensions of the array used for stimulation of the fingertips and tongue described by Bach-y-Rita, Kaczmarek and Haase[43][61].

During testing of the prototype, a concentric ring electrode pair was made from scrap metal (shown in photo P3 in the appendix). These electrodes were not meant to be ideal, they were a way to test the stimulator, when no other electrode materials were available. For the return electrode, a metal ring was used (probably zinc plated iron), with an outer diameter of 9.1 mm and an inner diameter of 4.1 mm (65.0-13.2 = 51.8 mm^2). A piece of a safety pin (probably steel) with a diameter of 1.1 mm (1.0 mm^2) was used for the center (active) electrode, leaving an air gap of 4.1 - 1.1 = 3.0 mm. The electrodes were connected to copper wires from a solid core UTP cable (cat 5e).

11.3 Skin and electrode preparation

The goal of the protocol is to reduce skin resistance. According to K. A. Kaczmarek, preparation of the skin is a very important factor (personal communication, 28-jun-2013). Dirt increases resistance, and skin resistance is lowered with increased hydration. The following procedure was inspired by skin preparation procedures described in literature[25][61].

First, the skin was cleaned with water and soap, then with isopropanol. Finally, the skin was hydrated with tap water. Two concentric ring electrodes glued to a strip of leather were cleaned with ethanol, before being fixed on the lower arm by means of a leather belt (see photo P4 in the appendix). No electrolyte gel was used because buildup of sweat between the electrode and skin was expected to suffice[25].

11.4 Stimulator operation

The control module was extended with three colored LEDs to indicate module status (see the schematics in the lower half of S9 in the appendix). A red LED indicates the device is powered, a green LED indicates the system is ready for use (done booting), and a yellow LED indicates an output signal is being generated.

Before stimulation, the voltage cap can be set manually (potmeter), to protect the user from dangerous and painful currents due to component failure or errors in the design. However, if the potmeter resistance (of the voltage cap circuit) becomes to high, the LT1618 will attempt to increase the voltage to infinite, until it (and possibly other components) fry. Make sure the voltage divider is setup correctly before testing!.

The action of the current regulation potmeter is inverted (turning clockwise decreases current amplitude), before the experiment is started it should be verified that the regulator circuit output is at 0 mA, instead of the current cap set in hardware (as an extra safety measure).

During the experiment, the user can turn of the stimulation power at any time, by flipping a switch. Keypresses on a laptop (running on battery, not AC) connected to the control module (Raspberry Pi running testing software) over SSH, produce either a short train of pulses, or toggle the output of a continuous stimulation wave. The user can control the output current using the current regulation potmeter. User controls are shown in photo P5 (appendix).

12 Proof-of-concept - results

Under the testing conditions, the stimulator was able to produce a perceivable stimulus. However, the dynamic range was 0, as the lowest perceivable current producing a painful stinging sensation. This is not unexpected, as the output wave for testing was selected to be strong (easy to detect), and small electrodes are known to increase the chance of painful stimulation (as discussed section 7.3). Additionally, the surface of the center electrode was noticeably uneven, resulting in an uncomfortable sensation even without any electric stimulation. It has also been noted that stimulation pulses with duration of less than 0.5 ms are a good idea, otherwise the pain threshold drops more quickly than the sensation threshold[4], this too explains the observed dynamic range of 0.

More measurement are required to determine the exact output characteristics of the device during stimulation of a subject, but no equipment suitable for recording such data was available during the proof-of-concept experiments. Further testing of the prototype will focus on its ability to control frequency and pulse length, in order to verify that the output wave shape is generated as expected. Such testing would require better electrodes (size and materials). The selection of better electrode dimensions is covered in section 13.1.

13 Improvements - methods

The proof-of-concept sections show that the stimulator prototype was able to produce a perceptible sensation, but with a dynamic range of 0. In order to encode any data, the dynamic range must be increased. The goal of the following experiments is to improve the stimulator prototype, to make it suitable for experimentation with data transfer through the skin.

During the following experiments, an oscilloscope (Rigol DS1052E) was used to verify output peak shape visually. The following sections cover the improvement of electrodes and testing software, regulator module hardware optimization, output filter optimization, and alternative methods to fix electrodes on the forearm. Wave shapes for the following experiments are based on a stimulation wave shape described in literature[34]: a square wave of constant frequency (50 ms period, 20 Hz) with (software controlled) pulse lengths between 50 and 350 μs (duty cycle between 0.1% and 0.7%), with a user-controlled amplitude of 0-5 mA. The reason for not supporting 0-10 mA is explained in section 15. Before the stimulation experiments to examine the performance of the new electrodes, various aspects of the stimulator prototype were improved, as described in the following paragraphs.

During stimulation experiments, current could not be measured directly, because no available equipment was able to measure rapidly varying current. Where stimulation currents are noted, they were measured separately. The user controls the current manually by means of a potmeter. By simply leaving the potmeter at the same position after stimulation, the output circuit will attempt to maintain the stimulation current, even if the module output is connected to a different circuit (in this case, a circuit to measure current). This principle only works if the current was not limited by the device's maximum voltage during stimulation. After turning the device off, the electrodes and output filter were disconnected, and the switching switching circuit was bypassed, in order to make the device act as a DC current source. The output was connected to a 2K load, because at 2K the current can not be capped by the device's voltage limit. Current was measured using a multimeter connected in series with the 2K load.

13.1 Steel electrodes

The results of the first prototype tests indicated a need for better electrodes. The goal is to find electrode dimensions that facilitate comfortable electrocutaneous stimulation on the forearm, with an effective dynamic range greater than 0. According to K. A. Kaczmarek, optimal electrode size is best determined experimentally, but a center electrode diameter of 5 mm would be a sane starting point (personal communication, 29-jun-2013). The subjective performance of a range of concentric ring electrodes of varying dimensions will be compared in the next paragraphs. Dimensions were determined for four electrode pairs, as presented in table 13.1. A design sketch for the electrodes is shown in figure 13.1.

Table 13.1: Electrode dimensions.

Center electrodes:

ID	**Diameter**	**Surface**
1	4 mm	12.6 mm^2
2	5 mm	19.6 mm^2
3	6 mm	28.3 mm^2
4	7 mm	38.5 mm^2

Return electrodes:

ID	**Inner diameter**	**Outer diameter**	**Surface**
1	6.5 mm	8.6 mm	24.9 mm^2
2	7.5 mm	10.5 mm	42.4 mm^2
3	8.5 mm	12.3 mm	62.0 mm^2
4	9.5 mm	14.0 mm	83.0 mm^2

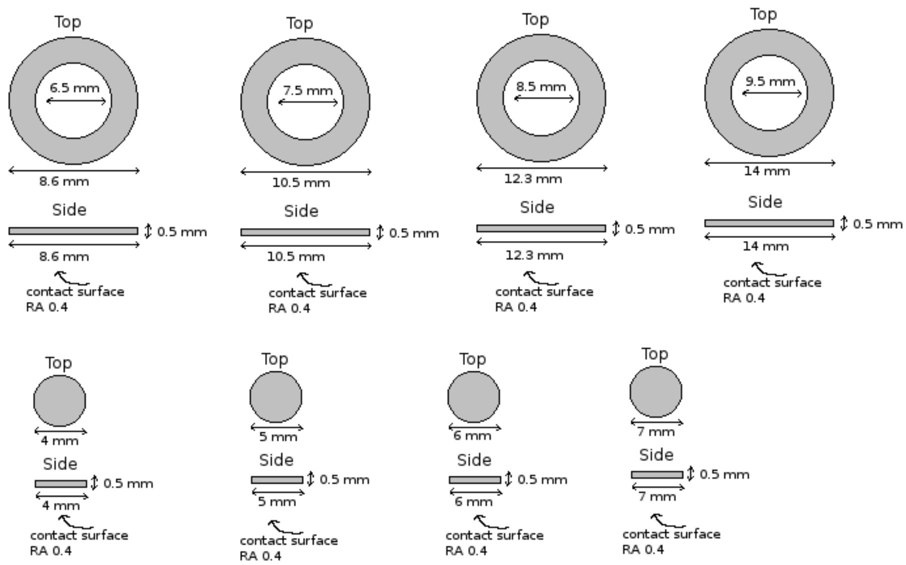


Figure 13.1: Design sketch for electrodes of various sizes.

A number of concentric ring electrode pairs (pairs of inner electrodes and return ring electrodes) were manufactured (grade 316 stainless steel) for the experimental determination of optimal electrode dimensions. The range of steel electrodes is shown in figure 13.2.

Figure 13.2: Steel electrodes of various sizes.

Stainless steel (grade 316) electrodes can not be soldered to copper wires using the same methods used for soldering electronics components and copper (relatively low temperature, (raisin-core) lead/tin solder, isopropanol flux). Attempts to connect a copper wire to the electrodes using a conducting (silver) paste to ensure a conducting contact surface, and subsequently fixing the wire to the electrode with a cover of non-conducting glue were unsuccessful.

Copper wires (from cat 5e UTP cable) were successfully soldered to the steel electrodes using the following method: After cleaning the electrode surface with isopropanol, a droplet of 6M HCl (6 moles/liter hydrochloric acid) was applied to damage the electrode surface. After a few seconds, the electrode was heated using a regular soldering iron and the damaged spot (on the droplet of HCl, without removing it) on the electrode was tinned using common soldering tin (Sn/Pb 60/40, 2.0% flux, 0.7 mm). The electrode was cleaned with water to remove residual HCl. After these preparations, a tinned copper wire was soldered to the tinned spot on the electrode.

The four electrode pairs that were selected for use in the following experiments are shown in figure 13.3. A close-up of a pair of concentric ring electrodes is shown in photo P10 (appendix). Color coding of the wires is presented in the following table:

Table 13.2: Wire colors for electrodes used for experiments. Size ID is relative, smaller number is smaller electrode.

Center	**Return**	**Size ID**
bluewhite	greenwhite	1
brown	brownwhite	2
orange	orangewhite	3
green	blue	4

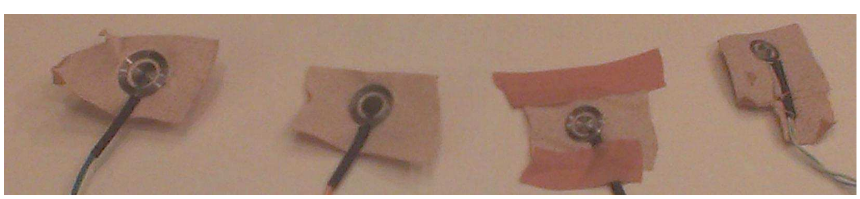


Figure 13.3: Pairs of steel electrodes, left to right: ID 4, ID 3, ID 2, ID 1.

13.2 Software improvements

The testing software was modified to allow control over the duty cycle during experiments. Functions were added to allow a user to increase and decrease the duty cycle of an active stimulation wave (within bounds determined by two constants), with a pre-determined step size, by means of key presses. A function was also included to reset the duty cycle to a default value.

13.3 Output wave shape

The previous experiments to confirm the quality of the output signal (described in section 10.2) were performed based on an output signal with a duty cycle much higher than the ones described by Szeto and Lyman[34].

During experimentation, it was found that the output load should be kept small, as a large load (10K) increases the power through the LT1618 (voltage max caps the current) up to the point it overheats and dies (if the chip is used without any cooling, as it was during the experiments). Subsequent experiments used a lower duty cycle (up to 20, if a crude and obvious wave was required for visual inspection). The load used for subsequent experiments was reduced to 1K, 2K, 3.2K, or 6.6K depending on the situation.

To verify the output signal is still of adequate quality under the new conditions (20 Hz, duty cycle 0.1%-1.0%), the output signal was inspected visually again. The output wave shape quality decreased dramatically for small duty cycles. Following methods to verify module described in previous sections, it was determined that the signal looked as expected up to the switching module (although duty cycles below about 0.2% at 20 Hz result in unstable output, possibly indicating a limitation in the RPi.GPIO python software lib[82]), the wave was distorted severely by the regulation module. In order to improve the output quality of this module, the high-pass filter was temporarily removed for experimental optimization of the regulator circuit. Results are presented in section 14.1.

13.4 Capacitive coupling

Visual verification of the output signal after optimization of the regulator module indicated the output signal was distorted by the high-pass filter. If the high-pass filter is modifying the signal, its RC value should be increased. Although the previous filter was determined to be adequate for a 20 Hz wave with a higher duty cycle, a lower duty cycle (of about 0.2%) requires a filter with a cutoff frequency of about 20 * 0.002 = 0.04 Hz. The 1 MΩ resistor was left in place, as the capacitor was replaced (new value: 2.2 μF. Cutoff frequency: 0.07 Hz). Visual inspection indicated the new circuit resulted in a stable output wave of adequate quality, for duty cycles of 0.3% and higher. Waves with a lower duty cycle became unstable (erratic frequency as well as peak amplitude and wave shape), this phenomenon was familiar because it was also observed during the testing of modules in the previous section (13.3), it is likely due to software limitations. Such limitations are not a problem for the experiments described herein, but they might be important to consider in future versions of the software.

13.5 Electrode fixation

The center and return electrodes used in the proof-of-concept experiments were glued to leather to fix their relative positions, the pair was then secured on the forearm with a belt. For the experimentation with the new electrodes, no electrode pairs were glued, to allow for future experimentation with different pairs. Instead, a sticky tape meant for fixing bandages to skin was chosen. The resistance of the electrode pairs (on sticky tape) was measured with a multimeter (out of bounds, ¿ 2 MΩ) to verify no shorting occurred between the electrodes.

As discussed previously, the entire electrode surface has to be in contact with the skin. The electrodes were placed on the volar forearm. The electrodes were fixed using tape, but this method did not lead to reliable and consistent electrode-skin contact. Wrapping bandages tightly around the arm with the electrodes improved contact. A different approach was to secure electrodes first with tape, then press them on the skin with a rubber band. The latter approach turned out to be more practical. This method can be seen in photos P8 and P9 (in the appendix).

13.6 Stimulator experiments

Whether negative or positive stimulation pulses are more effective depends on locus. According to K. A. Kaczmarek, negative pulses are likely to produce better results than positive ones for stimulation of the forearm (personal communication, 28-jun-2013). To verify this, the following experiments were performed twice, once for positive current pulses, and once for negative ones.

To compare electrode comfort, the following experiments were repeated for four electrode pairs, placed on various locations on the volar forearm (see photos P8 and P9 in the appendix).

The experiments started out from the following situation: a continuous 20 Hz stimulation wave with a duty cycle of 0.6% (which could be turned on or off by the subject). The stimulation current was increased from 0 to a perceptible level by the subject. The duty cycle (pulse duration, in a range of 0.1% 2.0%) was controlled by the subject, and the subjective sensations caused by the stimulation were noted.

Additionally, the effect of the high-pass filter (on stimulation quality and post-stimulation effects) was examined. The stimulation experiments were done with the smallest electrode pair in three locations on the volar forearm, both with negative and positive current pulses, and both with the high-pass filter in place and removed.

14 Improvements - results

The stimulator performance is evaluated in the following paragraphs. Photos P7 and P9 show the working improved stimulator prototype, schematics are presented in S9 (all situated in the appendix). Results of hardware optimization, as described in section 13, are presented first, followed by the subjective descriptions of stimulus quality for the electrode experiments. A number of phenomena described in literature has been observed during stimulation experiments, they have been described in section 14.4.

14.1 Output circuit optimization

A number of components impact the output wave shape of the regulated current source module (see C2, C3 and R4 in schematics S4, S5, S8 and S9). Initial experimentation showed the importance of the values for C2, C3 and R4. A smaller value for R4 resulted in a consistently better output signal, so it was removed. It was found that C3 should not be much greater than C2, and C3 should be large. C2 should be small. The optimal values were found to be: R4=0R, C3= 10 nF, C2=2.2nF. The following table lists the measurements that resulted in this conclusion:

Table 14.1: capacitor optimization experiments, tested with 20 Hz PWM, duty cycle 0.1%, load 2 red LEDs in series for additional visual feedback.

C3 value	C2 value	Peak shape
470 pF	10 nF	half square
10 nF	10 nF	half square
100 nF	10 nF	flat line
47 nF	10 nF	flat line
22 nF	10 nF	flat line
10 nF	470 pF	Shape OK, with some fluctuations
470 pF	470 pF	Very unstable
10 nF	4.7 nF	peak shape almost OK
22 nF	4.7 nF	flat line, incidental single peaks
10 nF	2.2 nF	Shape OK, relatively stable
10 nF	470 pF	Shape OK, with some fluctuations
22 nF	2.2 nF	incidental peaks

14.2 DC vs zero-DC

Removing the high-pass filter exposes the subject to a net-DC current, which is more likely to cause skin damage. Experiments indicate the same stimulation wave is perceived as much stronger, if the high-pass filter is removed. The sensation has more of a stinging quality, and it is more likely to cause a painful sensation in comparison to stimulation with the high-pass filter. Post-stimulation redness after zero-DC stimulation fades relatively quickly, but post-stimulation discoloration as a result of exposure to a net-DC current, even for a short period (tens of seconds), takes days to fade completely.

For a single experiment, the perceived intensity of a 100% duty cycle output was examined briefly (no pulses, just a constant current). Although increasing the duty cycle causes an increasingly strong sensation, a continuous (non-pulsed) DC current is much less effective, it causes it a significantly weaker sensation.

14.3 Electrode pair comparison

The skin on the volar forearm was prepared as described in section 10.3, electrodes were fixed on the arm using methods described in section 13.5. Experiments were performed as described in section 13.6 (four electrode pairs, different locations on volar forearm, subject controls current and duty cycle of a continuous 20 Hz PWM wave). Results are presented in the following table:

Table 14.2: Perceived stimuli per electrode. Electrode size ID (ID) is relative, smaller number refers to smaller electrodes. Current and duty cycle controlled by subject. 20 Hz PWM wave. Polarity refers to polarity of center electrodes. Current refers to the current selected for stimulation by the subject.

ID	Polarity	Current	Sensation	Notes
1	-		Imperceptible	
1	+		Imperceptible	
2	-	1.06 mA	Prickly	Slightly more comfortable than + pulses
2	+	1.61 mA	Prickly	Intensity changes with duty
3	-	1.70 mA	Range	Increasing of duty becomes painful quickly
3	+	1.54 mA	Prickly	Relatively comfortable, best dynamic range
4	-		Imperceptible	
4	+	2.35	Imperceptible	Sudden muscle contraction at 1.5% duty

14.4 Notable observations

Larger electrodes resulted in more comfortable stimuli, as expected.

The electrode location on the skin makes a significant difference: the small electrode pair (ID 1, see table 13.1) has been used to transfer perceptible stimuli, during DC vs zero-DC experiments (section 14.2), but as shown in table 14.2, no stimuli were perceived during the electrode pair comparison experiments. The only things that changed (in comparison to experiments were the small pair worked) were the exact location on the forearm, and possibly the contact between the electrodes and the skin (though unlikely, as the electrodes were secured tight enough to leave an impression in the skin). Therefore, this effect is likely due to variations in skin properties like resistance (which depends on skin preparation and thickness) and receptor contents. Other skin properties might also affect the density of the current through the skin.

Electrode pair 4 (the largest electrodes) were placed relatively low on the forearm (closer to the wrist). Although no other stimuli were perceptible, a muscle contraction of the hand resulted from positive current pulses, when the duty cycle was increased to 1.5% (corresponding to a pulse duration of 750 μs).

The most useful results (from the perspective of data encoding) were obtained with electrode pair 3. A notably better dynamic range was observed with positive stimulation through this electrode pair: a larger range of duty cycles yielded a range of perceived intensities that were not considered painful (maybe a little bit prickly). However, switching this electrode pair to negative current had a different effect: at low (barely perceptible) stimulation currents, the effect of duty cycle on perceived intensity was much stronger, quickly resulting in sensations strong enough to be regarded painful. This occurred with duty cycles as low as 1.0%. Additionally, an occasional single sensation of pressure was felt. Increasing the stimulation current to about 1.70 mA resulted in a range of sensations (indicated as "range" in the sensations column in table 14.2), such sensations were not perceived in any other stimulation experiment described herein. Increasing the duty cycle resulted in the occurrence of the following sensations: apart from the familiar prickly sensation, rapid tapping (pressure) was felt, followed by a sort of strange (not quite comfortable) sensation, best described as something between tickling and itching.

The effect of sensory adaptation was encountered during stimulation through electrode pair 1. Adaptation seems to occur faster and stronger if a stimulus is barely detectable: if the current was increased to just over the threshold of perception, the stimuli disappeared within seconds. If the current was increased to barely to the new threshold perception, it moved again. This way, a stimulation current that resulted directly in pain previously, became barely perceptible. If the stimulation wave was turned off and on again (without changing the current), the stimulus was perceived as a more intense one, once again.

The importance of using zero-DC stimulation waves was confirmed experimentally: net DC current pulses result in significantly more irritation of the skin (under the center electrode), and less comfortable sensations, than zero-DC current pulses.

15 Stimulator design - discussion

The goal was to design and build a stimulator prototype capable of producing perceptible stimuli through the skin, to enable researchers and hobbyists (with limited funding) to research new man-machine interfaces through means of electrotactile stimulation. The output requirement of the device (shown as "Stimulator capabilities" in table 6.1) was defined as "Adequate quality of stimulator output.". The high-level overview of the outcome regarding stimulator requirements is presented in table 15.1.

In section 6.2, it was attempted to define sane values for stimulation wave parameters, based on information presented in literature. Obviously, the goal in practice was not to build a stimulator capable of delivering all stimuli defined in table 6.3, but rather to build a stimulator capable of delivering stimuli through the skin, with an intensity controlled by software (with a dynamic range >0). Not all output capabilities of the prototype match the ones listed in table 6.3, the difference is shown in table 15.2.

Table 15.1: Stimulator requirements: outcome.

Description	**Priority**	**Outcome**
Safety	Highest	No unexpected injuries were sustained
Stimulator capabilities	High	Stimuli with a dynamic range >0 perceived
Cost	Medium	A working prototype was built without external funding
Uncomplicated	Low	Common ICs were used to reduce circuit complexity
Component quality	Lowest	Undetermined, number of experiments to small

Table 15.2: Measured stimulator output capabilities.

Parameter	**Supported range**	**Actual values during experiments**
Current	0-10 mA	0-5 mA
Voltage	0-30 V	0-28 V
Wave frequency	0-1000 Hz	20, 50 Hz
Pulse length	2-1000 (step 0.2) μs	50-1000 (step 50) μs

On the subject of safety: even a stimulator running on batteries (not connected to mains in any way) could cause damage under certain conditions. Though steps were taken to minimize the risk of injury, some (hypothetical) risks can not be prevented in hardware, a user has to take care when programming the device (no such problems occurred during any of the experiments).

The reason for limiting the stimulation current to 0-5 mA was to increase the practical resolution of manual current control, within a range of useful values. The range most useful during stimulation experiments was 1-3 mA, therefore 0-5 mA was deemed more appropriate than 0-10 mA.

The decision to aim for a stimulator design capable of delivering a maximum of about 30V was expected to result in problems with high skin resistance. It is very likely that the stimulator was not able to deliver a perceptible stimulus during several experiments, because the stimulator voltage limit was reached (due to inconsistent skin resistance on the forearm).

During the proof-of-concept and stimulator performance experiments, stimulation waves of 50 Hz and 20 Hz were used respectively. The stimulator modules have been confirmed to be able to produce adequate output waves in the range of 1 to 1000 Hz (in section 10).

The step size of $50 \mu s$ during experiments was chosen because it yielded clear and discrete variations in perceived intensity, step size could be decreased in software without any problems. However, the quality of pulses (determined visually) started to decrease as the pulse length dropped below 150 μs.

15.1 Limitations of the experiments

Comfort and type of sensations caused by electrocutaneous stimulation are inherently qualitative (subjective) properties, but measurements of voltage and current during stimulation help to determine if the abilities of the stimulator hardware are sufficient to satisfy the stimulator requirements presented in sections 6.1 and 6.2. For instance, if a stimulation signal is not felt, is this because a current limit or a voltage limit is reached? Maybe the electrodes are not making contact? Measuring the electrical properties of the signal actually passed through the skin becomes valuable.

However, the visual feedback from the oscilloscope did not match the sensations felt on the skin reliably. During most of the stimulation experiments, a peak of about the maximum voltage was shown on the scope, but the voltage limit was probably not reached, as increasing the current using the potmeter still led to a more intense sensation, for quite a range (from barely perceptible to painful). Though an increased peak width might also cause an increased intensity of the sensation (in this hypothetical case, increasing the current would in fact increase pulse width as the voltage limit is reached), the pulse length was not (visibly) increased in reaction to current control. The pulse length did change as expected with duty cycle. Therefore, the oscilloscope-based method was not a reliable method to determine actual stimulation voltage.

As explained in section 13.0, taking current measurements was a convoluted process due to a lack of suitable measuring equipment. The method of measuring current also assumes that the maximum stimulation voltage was not reached during stimulation, but this is not a realistic assumption.

In cases where no stimulation signal was perceptible, this was likely the case because the maximum voltage of the stimulator had been reached. Chances are that the actual stimulation current was lower than expected from the setting on the current control potmeter, because the voltage limit was already reached (see section 10.2.2). This is very likely because the perceptible stimulations have shown that stimulation currents above 2 mA (especially through the smallest electrode pair) are probably very clear, possibly even painful. The positive stimulation experiment (electrode pair 4, as shown in table 14.2) showed that an increase in duty cycle produced an effect, whereas increasing the current did not do anything, likely because the output current was not actually increased.

16 Future experiments

The stimulator prototype described herein can be used for a number of potentially interesting experiments. Although such experiments fall beyond the scope of this thesis, the following paragraphs list a number of subjects that entice future research. Note that measuring equipment suitable for recording voltage and current during stimulation sessions would make subsequent experimentation easier and more reliable: observed phenomena may be the result of a number of variables, a reliable way to measuring voltage and current would reduce the number of unknown factors significantly.

Experiments to compare the perceived effects of different wave shapes (frequencies) would be interesting, and the stimulator prototype would not require any significant hardware modification (though a bigger RC value for the high pass filter would be desirable to make it more suitable for high-frequency waves with low duty cycles).

Electrode location seems to have a significant impact on the effect of a electric stimulus: the muscle contractions produced by positive stimulation of electrode pair 4 are likely due to their position on the arm. It would be interesting to study the effects of placing the electrode pairs at different locations on the skin, not necessarily limited to the skin of the volar forearm.

The limitations in output wave shape (reduced performance at very low duty cycles) are probably due to limitations of the python library used in the testing software. It is likely that a re-write of the testing software in a language like C could solve such problems adequately. If the output signal suffers from timing issues, modifications to the kernel might also be an option.

The stimulation experiments described herein were only performed on one person (the author), it might be interesting to test the perceived effects of the stimulator on multiple subjects in the future: but only after wave parameters have been defined that result in consistently comfortable stimuli.

The stimulation experiments with electrode pair 3 show a range of sensations caused by positive sensations, more experimentation is required to control (and separate, if so required) the perceived sensations for purposes of data encoding.

16.1 Module optimization

The most important limiting factor in this prototype is the output voltage limit, it has proven to be just barely enough for perceptible transcutaneous stimulation on the forearm. This problem can be solved by reducing the need for a high voltage (by minimizing skin resistance), or by replacing the module with a circuit that allows for a higher maximum voltage. In that case, all other modules could remain unchanged (the optocoupler in the switching circuit should be able to handle the new voltage though). With the prototype circuit, the LT1618 was not pushed to its voltage limit. It might be possible to squeeze a higher maximum voltage (about 5V) out of the device, but the final experiments were performed on the very last LT1618 available to the project, and this was not attempted.

Other modules could also be optimized. For instance, software control over current could be added using a high-frequency PWM signal through a low-pass filter (effectively an improvised DA converter[79]) on the voltage control pin of the LT1618, or, the Raspberry pi could be replaced with any chip capable of producing the desired PWM output signal.

16.2 More electrode experiments

Electrodes impact the perceived stimulus quality significantly, but only a limited number of experiments to examine different electrodes at different locations were possible within the scope of this project. It could be interesting to examine the performance of different combinations of center and return electrodes.

Using multiple center electrodes could also be interesting: electrodes could switch between active mode and return mode. Only one electrode would have to be active at the same time. An exploration of the possibilities of multiple simultaneously active electrodes would be an important step in future research, but this would likely require separate current sources for each electrode.

16.3 Experiments with a transcutaneous display

Once a combination of electrodes and stimulation waves are found that result in consistently comfortable sessions of stimulation, a wave property like frequency or duty cycle could be use to encode data. The possibilities of programs utilizing the principle of brain plasticity to communicate data to the human in a new encoding, through a transcutaneous display, is one of the reasons to design and build a transcutaneous stimulator in the first place.

Regardless of the application design, it can be hard for a user to learn to interpret a new type of information encoding. When a new code is presented to the brain, the key to efficient learning is likely the establishment of an effective feedback loop. It allows the brain to learn to recognize (and interpret) the new patterns a "natural" way, this is especially true for input devices that record information from the environment.

17 Conclusion

Electronics have become an integrated part of the contemporary environment. Humans and machines communicate through an interface, which effectively translates input and output between systems. The range of possible interactions between man and machine are therefore determined by the specifications of the interface. Traditional interfaces commonly use a (combination of) visual and auditory components to provide output from the machine, as input for the human. However, the tactile sense is also believed to be a suitable human input channel. The visual, tactile, and auditory senses are all sensitive to a characteristic ranges of sensory inputs, as determined by the physical properties of all receptors, afferents, and subsequential CNS processing capabilities involved in the respective sensory system. Although all receptors and afferents are already in place, the mechanism of brain plasticity allows a range of fundamentally different interpretations of input patterns by the CNS, after a period of training. Because the function of a man-machine interface is to translate between two systems (each with their own characteristics), awareness of the properties of both is important, and current interfaces commonly use readily available (familiar, previously learned) patterns to encode data: a visual display uses geometric shapes and "written" characters, instead of something like barcodes. To determine the best sense(s) to target when designing a display to get information into the human, functional demands of the interface have to be considered, as well as the properties of all available input channels (currently, the senses of vision, hearing and touch). The following conclusion can be reached:

Examining the fundamental data processing capabilities (strengths and limitations) of the human brain is a step towards better man-machine interaction.

Researching the mechanisms of sensory substitution, and the exploration of capabilities and limits of CNS can be done non-invasively with electrocutaneous displays: the brain mechanisms discovered will not be limited to cutaneous displays, instead they will generally hold for input provided to the CNS. The principles of brain plasticity (the brain is able to learn to comprehend new types of input patterns) are not limited to (electro)cutaneous displays, the principles will be applicable to invasive methods of providing inputs to the sensory system.

Cutaneous displays have been researched for a relatively long time, but they have not become common commodities. The lack of high-resolution cutaneous displays on the market could partly be due to the fact that no advanced coding scheme, comparable to the ability to understand text visually, interpreted through the skin is commonly learned by humans, to take advantage of for interface design. Learning a new complex coding scheme takes an unpractical amount of training time. It is hard to design an experimental setup to find the optimal means of transferring information via the tactile system, without being hindered by the fact that training the CNS to interpret complex encoding schemes, such as writing, from scratch costs more time and effort than could realistically be expected to be available for the majority of experiments. Experimental results presented in various publications give rise to the following hypothesis:

It is possible the optimal waveform/coding for electrocutaneous transfer of information has not yet been found, because of fundamental limitations of the experiments used to identify the most effective electrotactile codes: experiments described in literature used data (and codes) of insufficient complexity to reliably identify the best code for transferring complex data.

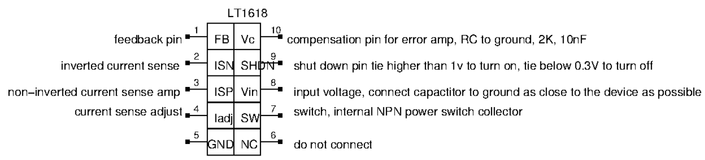
The identification of effective encoding schemes and applications would progress more rapidly if electrotactile displays would be easier to obtain: the greater the number of people who are experimenting with the technology, the faster the field will progress. Therefore, an important step towards making electrocutaneous displays more common is making them available to more researchers and early adopters: electrocutaneous stimulators need to become cheaper, and design specifications need to become easier to access. To this end, the process of designing a stimulator is presented herein. A single-electrode transcutaneous stimulator prototype was built and tested. It was found that it is possible to build a low-cost electrocutaneous stimulator from commonly available components that is able to deliver a range of perceptible stimuli through the skin of the volar forearm.

The stimulator design presented herein is not a finished product in its current state. The design has not yet been optimized for use by researchers or hobbyists expecting a fully functional (black box) stimulator, for the purpose of experimentation with cutaneous displays. An important reason for this statement is that stable, reproducible results can not be promised from the (small) number of stimulation experiments that were possible within the scope of this thesis. However, the design process of the transcutaneous stimulator described herein might be an interesting starting point for one considering to build such a device from scratch.

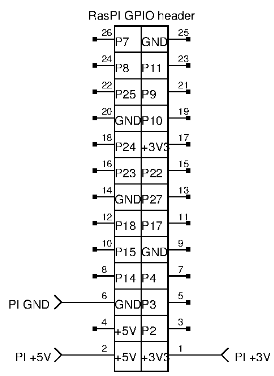
The long-term potential of man-machine interfaces that consider, and make use of the plastic capabilities of the human brain is simply incredible. Ultimately, the greatest challenge lies in finding the right applications to take advantage of such possibilities.

18 Appendix

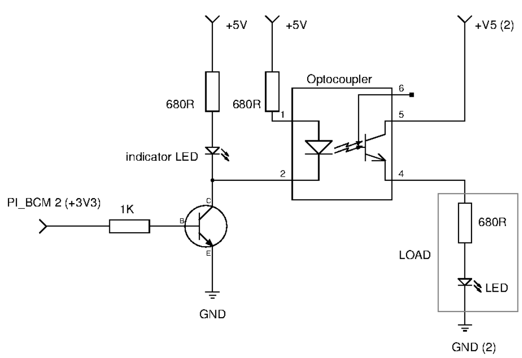
18.1 Schematics



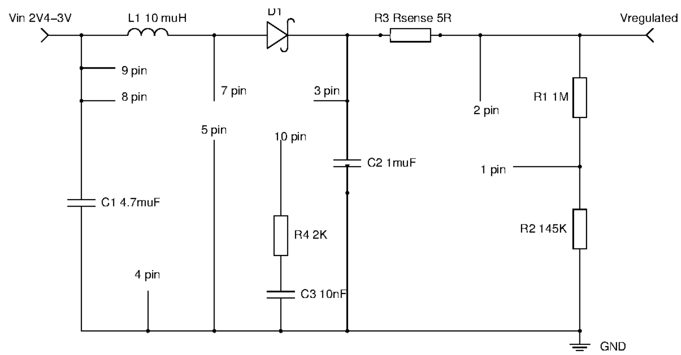
Schematics S1: LT1618 connections.



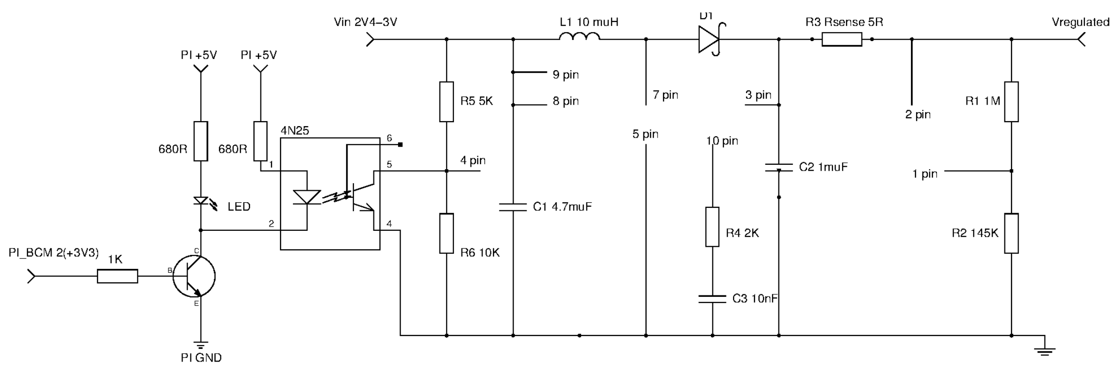
Schematics S2: Raspberri Pi (model B) connections.



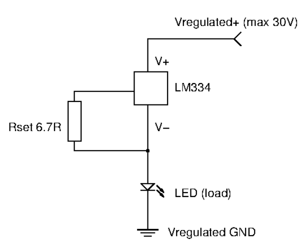
Schematics S3: Switching module.



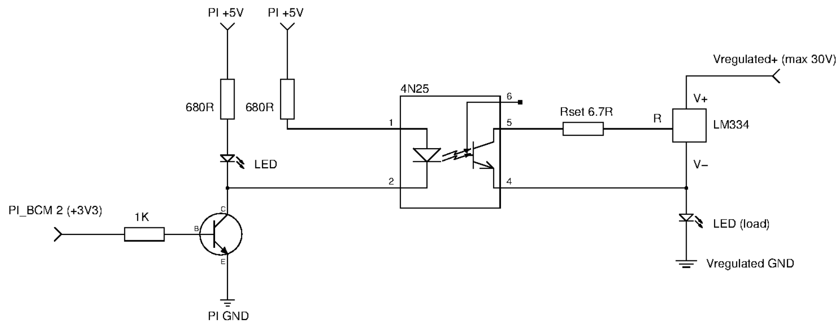
Schematics S4: LT1618 voltage/current source: voltage limit (R1/R2) = 10V, current limit(R3) = 10 mA.



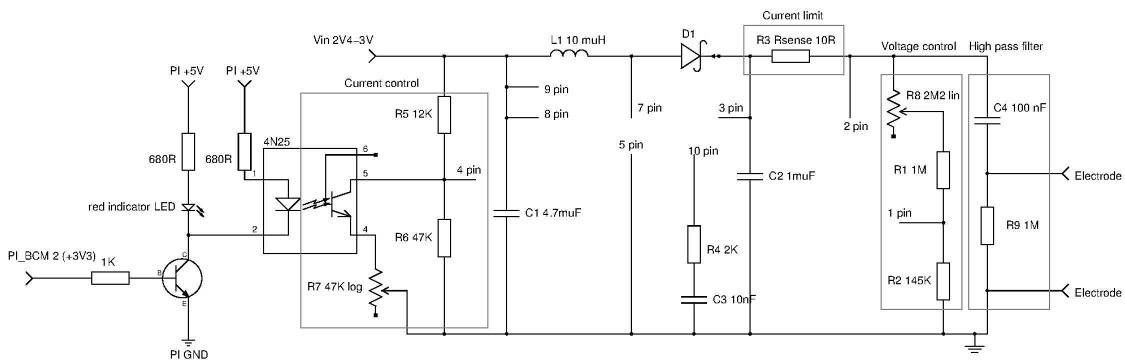
Schematics S5: LT1618 voltage/current source, connected to Rasperry pi output pin BCM 2 via switching circuit: voltage limit (R1/R2) = 10V, current limit(R3) = 10 mA.



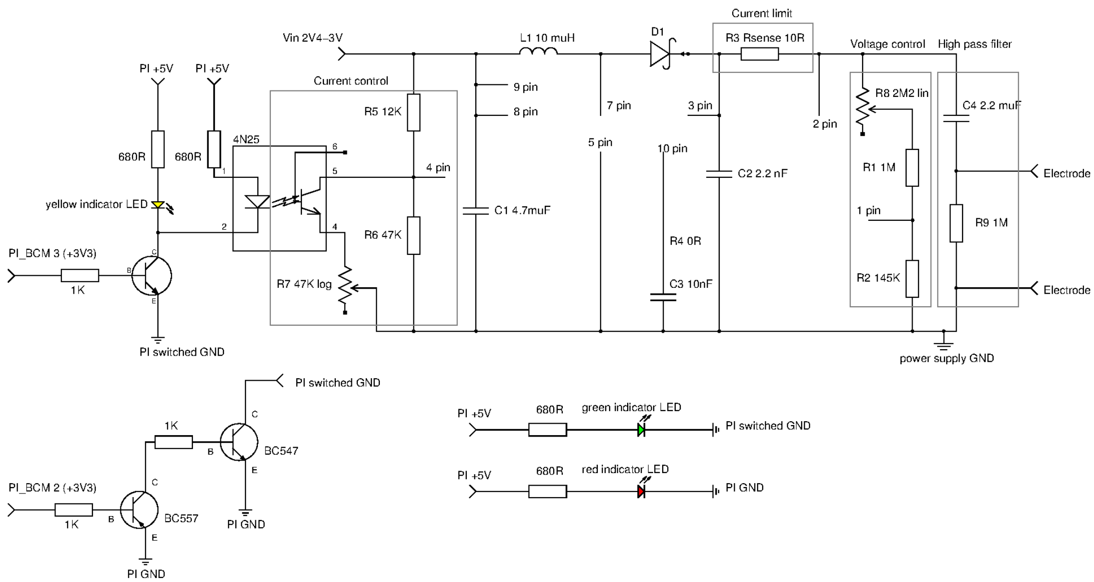
Schematics S6: A LM334 current source.



Schematics S7: A LM334 current source, connected to Rasperry pi output pin BCM 2 via switching circuit.



Schematics S8: Stimulator during proof-of-concept experiments. Indicated: High-pass filter, V control circuit (R8+R1)/R2 = 10V to 30V, A control circuit, current limit(R3)= 5 mA.



Schematics S9: Improved stimulator prototype, used for subsequent experiments. Indicated: High-pass filter, V control circuit (R8+R1)/R2 = 10V to 30V, A control circuit, current limit(R3)= 5 mA. Including circuits connected to Raspberry pi: A circuit to control power to circuits connected to other GPIO pins to prevent problems from erratic pin states during booting procedure (lower left), and additional status indication LEDs (lower right): red LED indicates power, green LED indicates device is done booting, yellow LED indicates PWM (switching) action.

18.2 Photos

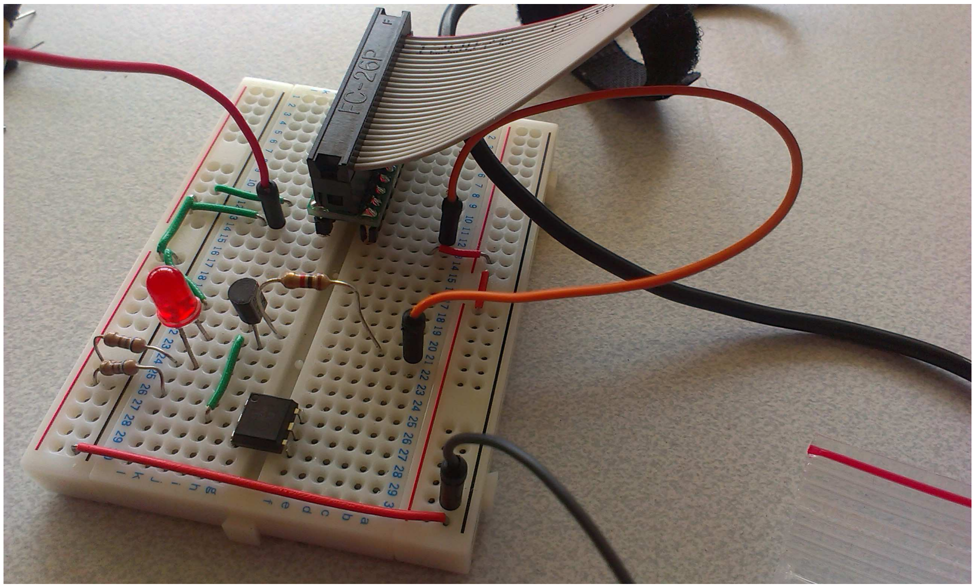


Photo P1: Switching module

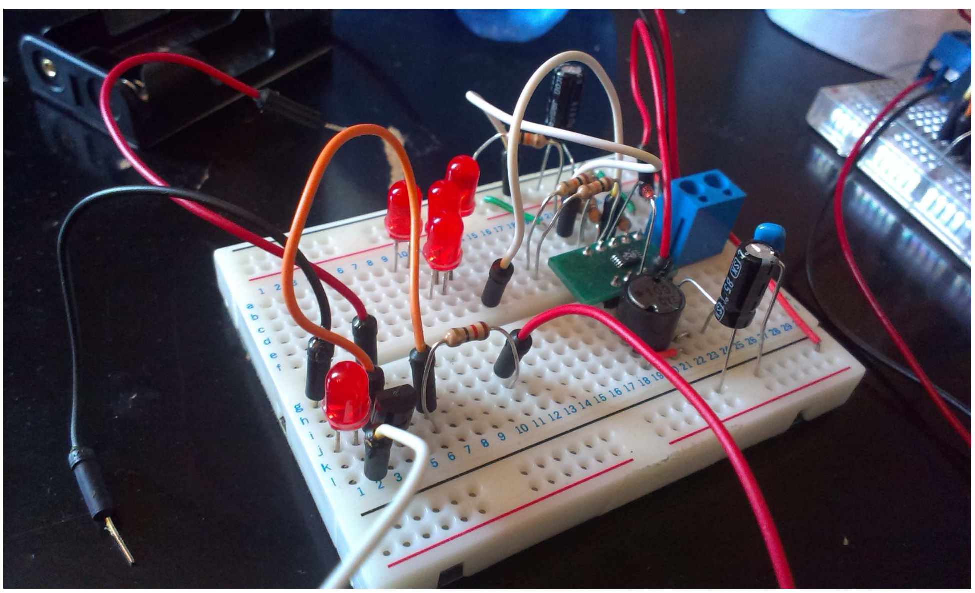


Photo P2: Current source modules based on LM334 (left) and LT1618 (right)

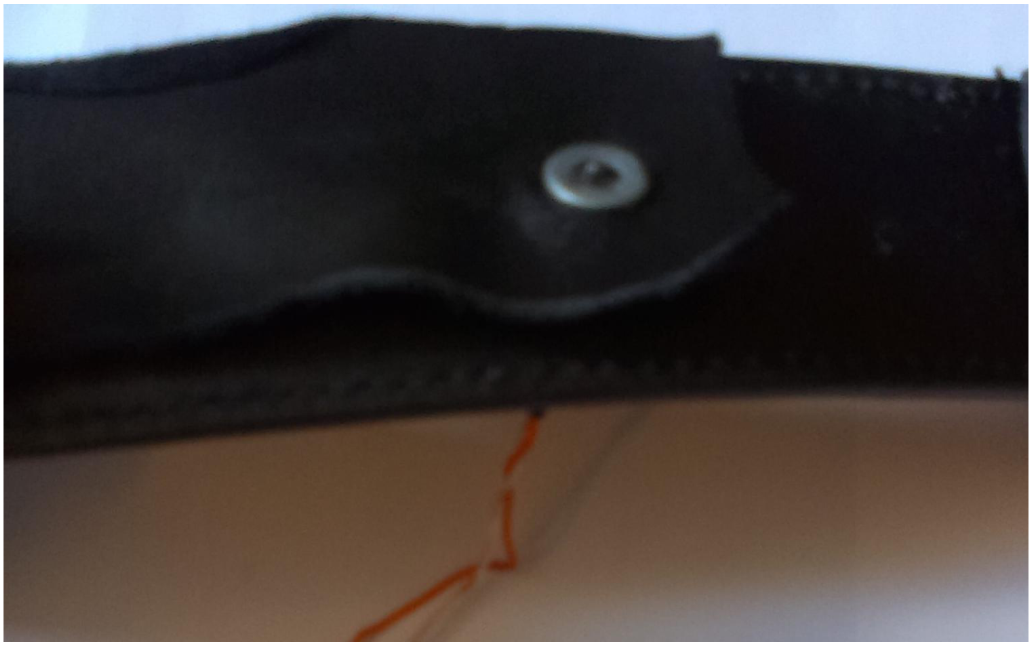


Photo P3: Proof-of-concept electrode pair

Photo P4: Proof-of-concept electrodes on forearm

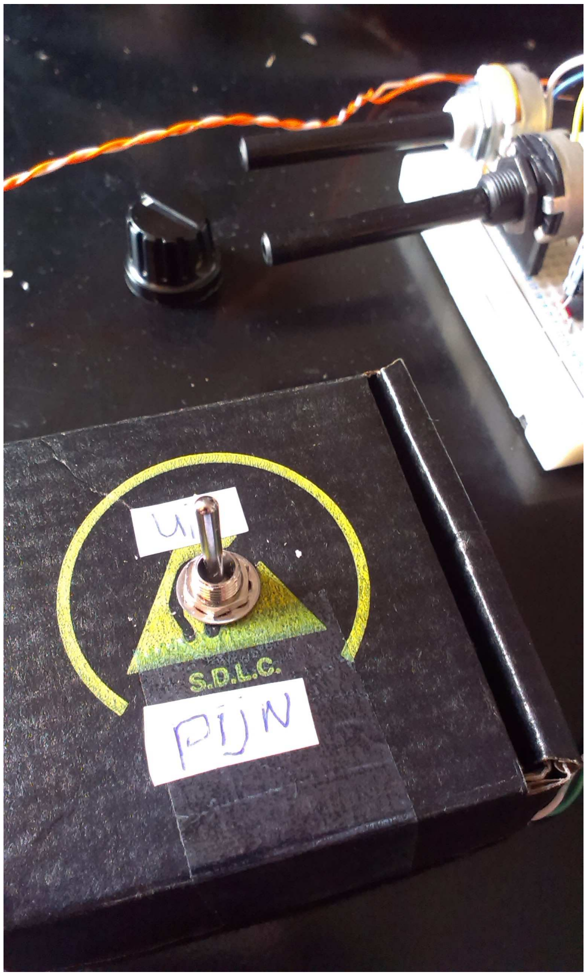


Photo P5: User controls

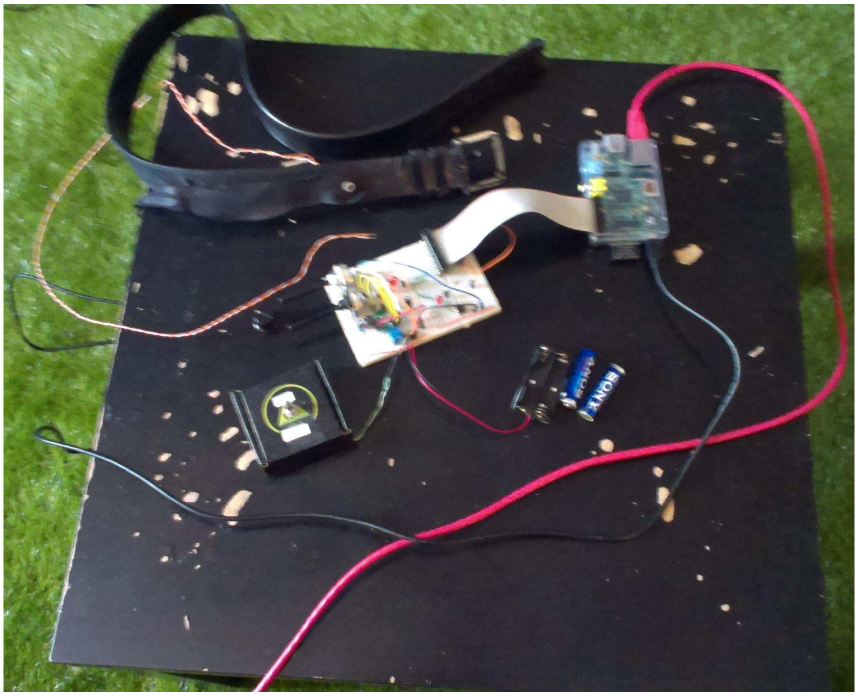


Photo P6: Proof-of-concept stimulator

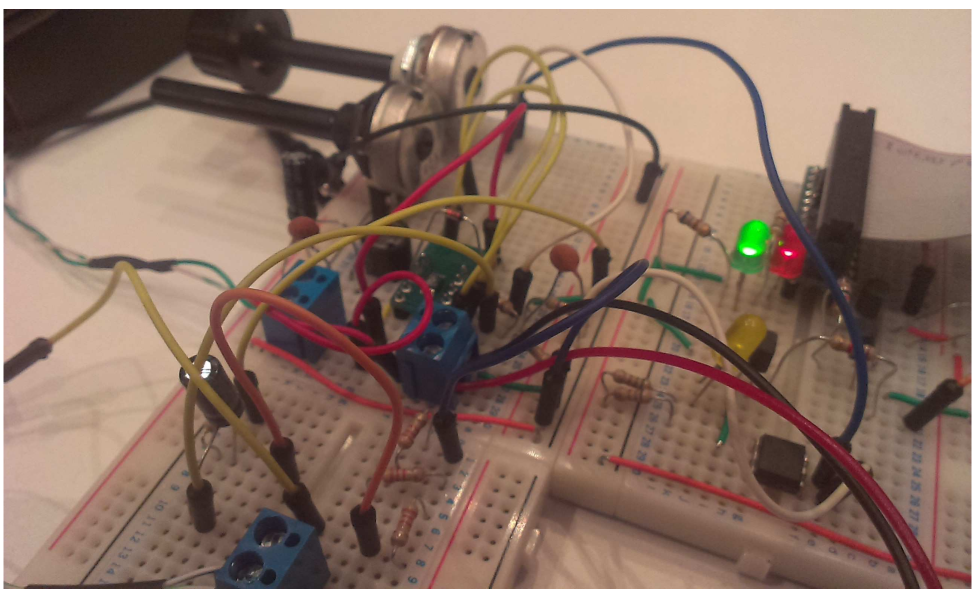


Photo P7: Improved stimulator prototype

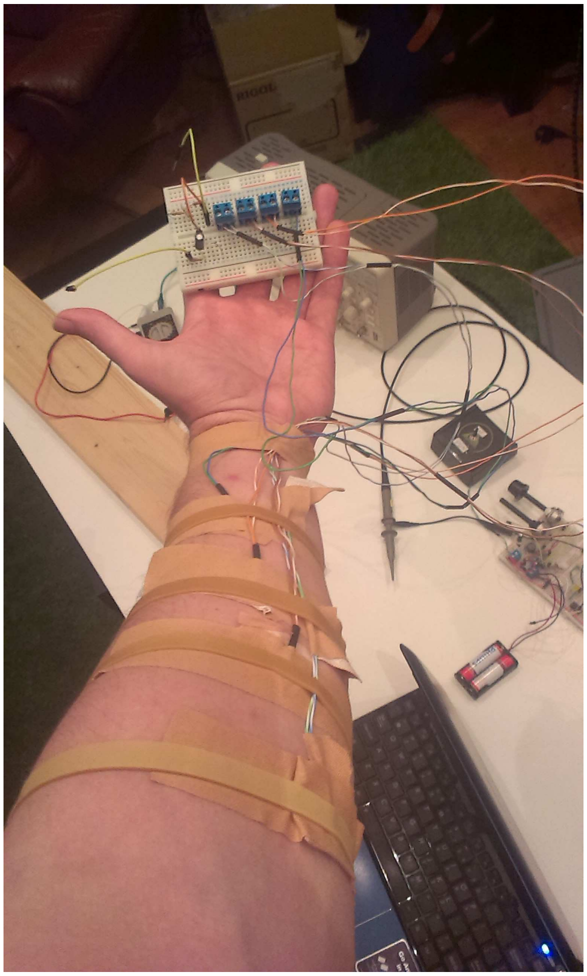


Photo P8: Steel electrodes on volar forearm

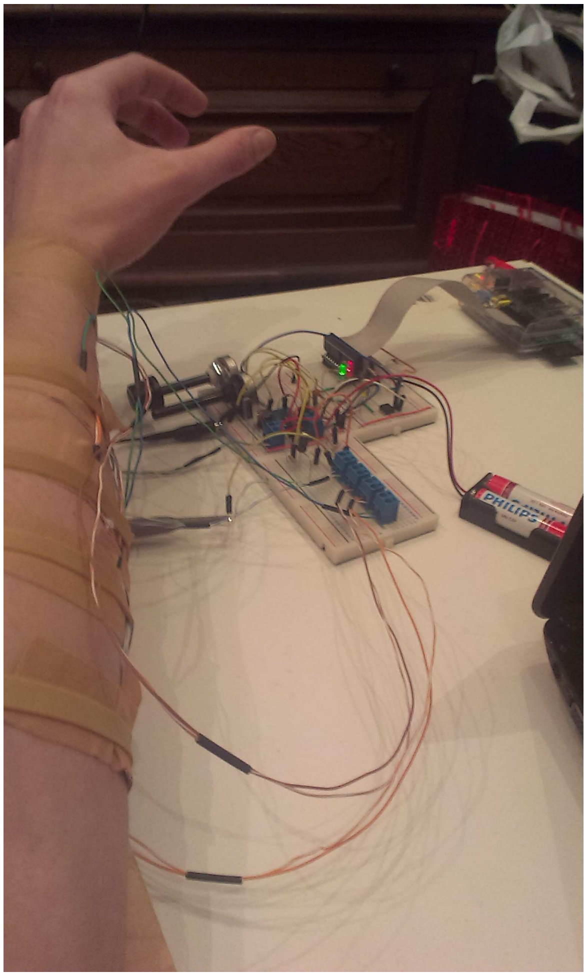


Photo P9: Improved stimulator prototype during experiments

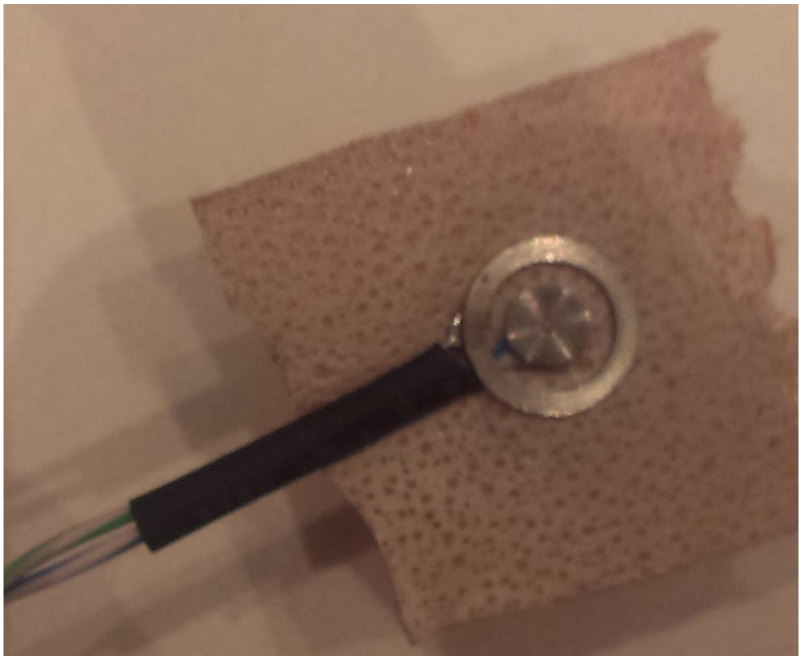


Photo P10: A steel concentric ring electrode pair.

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Acknowledgments

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