The tongue display unit (TDU) for electrotactile spatiotemporal pattern presentation

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Abstract

The Tongue Display Unit (TDU) is a 144-channel programmable pulse generator that delivers dc-balanced voltage pulses suitable for electrotactile (electrocutaneous) stimulation of the anterior-dorsal tongue, through a matrix of surface electrodes. This article reviews the theory of operation and a design overview of the TDU, as well as selected applications. These include sensory substitution, tactile information display and neurorehabilitation via induced neuroplasticity.

Keywords

1. Introduction

This paper describes the theory, design, and application of the Tongue Display Unit (TDU), a programmable electronic device developed by the author in 1999, and which has served as a general-purpose platform for studying the perceptual properties of electrotactile stimulation on the tongue. It has also been used to explore practical applications in sensory substitution and neurorehabilitation. Figure 1 shows a photograph of the TDU connected to a flexible-printed-circuit, 144-electrode array for stimulation of the dorsal surface of the tongue. The electrical stimulus to each electrode is individually controllable in real time.

1.1. Electrotactile stimulation

Electrotactile stimulation evokes tactile sensations within the skin at the location of a small, surface electrode, by passing a local electric current through the skin to stimulate cutaneous afferent nerve fibers. The percepts thus produced (vibration, tingle, pressure) can be used to communicate temporal and spatial information that is normally received through other sensory channels, such as vision, audition, proprioception and the vestibular sense [1–6]. Specific applications will be reviewed later in this article.

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1.2. Why the tongue?

1.2.1. Sensitivity—The tongue is an ideal site for electrotactile display [7]. It is highly mobile and very sensitive to touch, both in pressure sensitivity and spatial acuity [8–10]. It has a large representation in the brain, rivaling that of the hands, the primary human organ for exploration by touch [11]. The lips, palate and oral mucosa are also very sensitive to touch (with somewhat different sensory properties) and have been explored as sites for electrotactile display [12–16].

1.2.2. Electrical stability—Because of the tongue's protected location in the mouth, its hydration (and hence its electrical properties) is more consistent than those of the skin. In particular, the impedance of the electrode-tongue interface varies little with current, unlike cutaneous locations, where resistance drops sharply with increasing current [17–20].

Because electrode current rather than voltage is the better indicator of subcutaneous potential distribution and hence afferent nerve depolarization, electrotactile stimulation on the skin normally requires current-controlled (e.g. transconductance amplifier) circuitry [21,22]. On the tongue, however, simpler voltage-control circuitry suffices [23].

2. Theory of operation

This section will first describe the overall architecture of the TDU, followed by a discussion of the output waveform structure and how it activates the tongue cutaneosensory system to produce the desired tactile sensations. Next is a description of the output circuit responsible for delivering these pulses to an electrode array, with maximum simplicity and minimization of possible tissue irritation. Practical limitations of the TDU are described next, along with features enabling the stimulation waveform to be easily monitored. Finally, the TDU modes of operation and provisions for software control are summarized.

2.1. Architecture

The 12×12 electrode matrix (described more fully below) is functionally divided into four square, 36-electrode blocks (Figure 2). The electrodes in each block are sequentially pulsed in a raster-scanned format, as described later. The electrode blocks, A–D, dictate the core functional units of the TDU circuitry.

Figure 3 shows a block diagram of the TDU, which comprises five 8-bit microcontrollers, electrode driver output, power and communications circuits. The four microcontrollers labeled "Block" perform the low-level pulse generation functions for each grouping of 36 electrodes using waveform parameter information delivered from the main microcontroller. The latter handles communications to and from an external computer via an RS-232 serial link and allows for direct user control via a front panel button set and 4-line LCD display. Power is provided by an internal, rechargeable NiMH battery.

2.2. Output waveform structure

Like most electrotactile systems, the TDU delivers sequences of rectangular pulses with timing features assumed to correspond with relevant neurophysiologic time constants.

Because direct experimental data concerning the afferent neural response to tongue electrotactile stimulation are limited, e.g. [24], our comments are extrapolated from the general properties of cutaneous afferent fibers, supplemented by limited experimental data from mechanoreceptive afferents during electrotactile stimulation of primate fingertips [25]. The fundamental neurophysiological bases for specific design decisions must therefore be considered preliminary.

Positive stimulation pulses were chosen following unpublished pilot experiments showing lower sensory thresholds (similarly to [24]) and more comfortable sensory properties compared with negative pulses. (Positive pulses are also preferable on the fingertips, especially when small electrodes are used [26], whereas negative pulses are generally superior on other loci [3].)

The TDU output waveform (Figure 4, Table 1) is a complex train of pulses with two levels of pulse grouping (bursts). This section will consider this structure from smallest to largest time features.

2.2.1. Pulses and inner bursts—Individual Pulses of Width (PW), repeating with a period (PP), are grouped into *inner bursts*. The number of pulses in each inner burst is defined as the Inner Burst Number (IBN). Because the neural membrane acts approximately as a leaky integrator (parallel RC network), the charge from individual pulses summates to cause membrane depolarization which, if it exceeds a certain threshold value, causes an action potential to propagate unattenuated toward the spinal cord and brain [27] to effect sensation. The effective time constant of this integrator for human somatosensory fibers has been estimated at 70–900 μs and is dependent not only on membrane properties, but also on fiber orientation and electrode geometry [28, Chaps. 4 and 7].

Given this time dependency, the Pulse Amplitude (PA) voltage, PW and PP all determine whether an individual neuron will be stimulated. Because of the neural membrane's refractory period during which its sensitivity to re-stimulation is eliminated (approx. 0.5 ms) or elevated (several ms), only one action potential may be produced on a given fiber during each inner burst [28, p. 88]. In this way, these inner burst parameters affect primarily the sensory threshold and perceived intensity of the stimulation.

The neural membrane time constant decreases with increasing fiber diameter. Therefore, longer pulses may preferentially activate the smaller ($A\delta$, C) fibers subserving pain sensations relative to the tactile-sensation ($A\beta$) fibers [29]. As a result, both PW and inner burst structure (PP, IBN) may affect not only the intensity, but also the quality of the perceived electrotactile percept [30,31]. The intensity effect, however, is the most noticeable.

2.2.2. Outer bursts—A sequence of inner bursts, repeating with an inner-burst period of IBP, may be grouped into an *outer burst*. The number of inner bursts in an outer burst is the Outer Burst Number (OBN). While each inner burst results in at most one action potential, the time between inner bursts allows the nerve fiber to recover and therefore each outer burst may cause up to OBN action potentials. Furthermore, this neural activity occurs at a rate similar to that attainable by mechanical tactile stimuli [32]. Manipulating OBN and IBP can

change the perceived quality of the electrotactile sensation, as well as its ability to convey spatial information [33–35]. These non-intensive perceptual quality changes have been loosely described as tactile "colors" because they are readily discernible, although not nearly so much as for color vision [33,36]. For example, increasing pulse rate typically results in percept changes from pulsatile to vibration to pressure, whereas pulse width and burst structure can affect the comfort of the percept (vibration/tingle vs. pinprick) [37,38].

2.2.3. Base frequency—Finally, outer bursts may be interrupted by periodic pauses and repeat at the Outer Burst Period (OBP). The reciprocal of OBP is the base frequency of the stimulus waveform and this highest-level structure has a strong influence on one of the perceived qualities of the electrotactile sensation, sometimes called "pitch" in analogy to auditory perception of sinusoidal tone frequency [39,40]. Increasing OBN and 1/OBP also increases spatial pattern perception performance (probably via a sampling rate effect, see [35]), as well as the rate and magnitude of sensory adaptation [41].

2.3. Electrode sequencing

As indicated above, the 144 channels (each channel driving one electrode) are grouped into four 36-channel blocks (Figure 2). Each block drives one 6×6 region of the electrode array. The electrodes in each block are raster scanned in horizontal lines from left to right, top to bottom, as shown in Figure 2; on the tongue this corresponds to left-to-right, posterior to anterior. The onset of outer burst sequences between temporally-adjacent electrodes is the delay parameter ICP, for an inner-channel period (Figure 4). (Although ICP is technically not a period, we retain this nomenclature to be consistent with the software command set.) An inner burst on a given electrode must be complete before the temporally-adjacent electrode may begin its next inner burst. The beginning of the outer bursts in the four blocks is synchronized, so that four electrodes on the 12×12 array may be active at any time.

Only one electrode per block may be active at any time. The raster-scanning structure ensures that active electrodes are separated by 5 electrode center–center spaces, or approximately 11.6 mm, using the default electrode array. This separation allows unstimulated electrodes to act as the return current path (see the output circuit description, in Section 2.5). It is important to not have spatially-adjacent electrodes simultaneously active, because (1) there would then be an interrupted effective return path, potentially spreading the tactile sensation, and (2) the currents in the adjacent electrodes partially summate, yielding an abnormally strong tactile sensation. These comments result from unpublished pilot experiments; this is an area ripe for more extensive study.

There is a question whether raster scanning is the most effective pattern for static or dynamic spatial pattern perception. We did not test other scanning patterns on the tongue. We previously performed a preliminary experiment (unpublished) using four scan patterns (horizontal raster lines similarly to the TDU, vertical raster lines and two random scan patterns) on a 7×7 fingertip-explorable electrotactile array we tested earlier [35,42]. The subjects tested did not show any differences in static pattern perception, even for directional patterns (e.g. lines and arrows) that would most likely be affected by scan pattern. Dynamic patterns were not tested.

All waveform parameters in Figure 4 are manipulable via software commands to the TDU; new values become effective at the beginning of the first outer burst following the command. PA, PW, IBN and OBN may be set individually for each electrode. The burst timing parameters PP, IBP, OBP and ICP are common to all electrodes in the array.

Note that the present waveform timing nomenclature is different from that previously used by the author [21], in order to allow for more control over burst structure. Some of the terms are comparable, these being (new = old): PW = W, ICP = D, IBP = P, OBP = T, OBN = NPB. IBN and PP have no equivalents in the old nomenclature.

2.4. TDU timing limits

Table 1 shows the allowable timing and voltage values of TDU output pulses. This table also shows typical ranges, as well as a "standard" waveform which yields comfortable electrotactile sensations over a wide range of pulse amplitudes. This waveform was developed according to a magnitude-based dynamic range methodology previously reported [37]. Even if the parameters are within equipment limits, certain conditions apply to prevent corrupting the waveform burst structure. These limits, which appear in the Table 1 legend, are enforced by the TDU microcode.

2.5. Output circuit

Figure 5 shows (for one block of 36 channels) the essentials of the TDU output circuit, which controls the voltage and timing of the rectangular pulses sent to the electrode array. TDU output voltage is set by a Digital-to-Analog Converter (DAC) feeding an operational amplifier (OpAmp) buffer (U1). The output of U1 is directed to the appropriate output channel by an analog switch (U2). The Address lines feeding U2 choose which channel to pulse, while the Enable line determines the pulse and burst timing. Activity in these lines, along with the DAC, is synchronized by the μC, so that when a given channel is due to be active (i.e. receive a pulse), the correct voltage is delivered and the correct electrode is selected. The four TDU output blocks are controlled similarly (and synchronously), each block having its own DAC, buffer and analog switch. This hybrid analog-digital architecture results in fast switching of the variable-amplitude output pulses, while relaxing the speed and data-handling requirements of the DAC, a solution employed by other electrotactile researchers [43,44]. Described next are functions of the passive components in this circuit that manage the electrical characteristics of the output, performance limitations imposed by this architecture, and provisions for monitoring the TDU output in real time.

2.5.1. Passive components—The output circuit incorporates several features for controlling output resistance, providing a return path for the active electrode, and minimizing tongue tissue irritation. The output resistance for the active electrode is controlled primarily by R1 (the "on" resistance of U2 is   100 Ω). This 1.2 kΩ total resistance limits the current through U1 and U2 to prevent circuit damage should a short-circuit load be connected. It also provides a good quality of sensation over a variety of electrode sizes, although previous research [23] suggests that output resistance may not be critical in this matter.

Series capacitor C1 slightly shifts the mean output voltage so that the net dc current into the tongue electrode is extremely small. This minimizes the possibility of extracellular ion migration and electrochemical reactions that might cause tissue irritation. A separate capacitor C1 is used for each electrode so that dc balance is achieved *for each electrode*, even if the electrodes receive different voltages or waveforms. Note that the average TDU output (and therefore electrode) current is exactly zero with this circuit only if the electrode-tongue resistance is linear, because of the unbalanced pulse structure. Nonlinear resistive loads exhibit a "rectification effect" when driven with unbalanced waveforms [45]. For a discussion of this effect in the context of electrotactile stimulation and its possible relationship with skin or tissue irritation, see [19, Chap. 8]. Fortunately, the electrode-tongue interface resistance is relatively independent of current. In ten years of use in various experiments using approximately 200 human subjects (under protocol and oversight approved by the University of Wisconsin–Madison Health Sciences Institutional Review Board), none have reported tongue irritation. Prospective studies on the long-term effects of electrotactile tongue stimulation have not yet been performed.

The value of C1 (0.1 μF) represents a compromise between minimizing dV/dt voltage droop during stimulation pulses (a larger capacitance reduces droop; see Section 2.5.2.) and limiting the maximal delivered pulsatile charge to a safe level (4 μC) should a circuit failure occur [22]. This pulse charge is much less than the 290 μC upper limit recommended by *Underwriters Laboratories* (UL), a recognized electrical-safety certification organization. (The TDU itself has not been certified by UL or any other regulatory agency.)

Parallel resistor R2 serves as the primary sink for current returning to the TDU via the inactive electrodes. Because U2 disconnects inactive electrodes from U1 and R1, the effective TDU "output" resistance (assuming minimal drop in output capacitors C1) for the return current is 10 kΩ for each inactive channel. Adding to this the approximate electrode resistance of 6 kΩ per electrode (see later), the return-current resistance for each inactive electrode is 16 kΩ. Because the actual return path comprises a parallel combination of 35 TDU-electrode series-connected networks, the overall return resistance is approximately (16 kΩ)/35 = 457 Ω.

Parallel resistor R3 ensures a stable dc operating point (i.e. forces the mean output voltage to zero) even if the electrode is disconnected; its high value ensures that it has minimal effect on pulse voltage.

2.5.2. Performance limitations—The actual electrode voltage is somewhat less than that commanded by the software (by specification, 0–40 V) for three reasons: (1) There is a voltage drop across R1 of approximately 17% (once the exponential rise phase caused by electrode capacitance is over) due to voltage division, assuming a 6 kΩ tongue load and 1.2 kΩ TDU output resistance. (2) The presence of C1 slightly reduces the mean pulse voltage; the fraction of reduction is (1-Duty), where Duty = PW·OBN·IBN/OBP. For a typical stimulation waveform (PW = 50 μs,·OBN = 3, IBN = 1, OBP = 20 ms), duty is < 1%, so this pulse level reduction is minimal. (3) The nonzero return-path resistance reduces the effective voltage at the electrode-tongue interface, i.e. between the active electrode and the underlying large volume conductor (i.e. below the surface of the tongue; this "central" tongue voltage

will be similar to the mean whole-body voltage, assuming no possible current pathways other than the tongue). Note that while effects (1)–(2) represent reductions in the TDU output voltage and may be measured relative to the TDU ground, effect (3) represents a voltage difference between the body and the TDU ground and will not be reflected by measuring the output relative to the TDU ground. Fortunately, all three effects on a percentage basis remain relatively constant with changes in electrode voltage (because of the stable electrode-tongue resistance) and also with waveform timing (because of the small effect of the duty cycle). Nevertheless, the TDU user should be aware that the output voltage and pulse shape may be different from those expected and if in doubt measure these waveforms directly.

2.5.3. Measurement features—A voltage monitor circuit (one per block) is provided so that the user may observe (e.g. on an oscilloscope) the actual voltage delivered to the electrodes, which is recommended practice given the effects described in the above paragraph (only effects (1)–(2) are monitored). An OpAmp buffer (U3) amplifies the small voltage across R4 resulting from currents flowing through resistors R3. The buffer output (Monitor) waveform sequentially shows the (scaled) sum voltage of all electrodes in the block. Because the electrodes are pulsed individually, it is possible to separately measure the voltage on any given electrode while it is active. The small value of R4 relative to R3 ensures that there is minimal crosstalk between channels, owing to the small potential appearing at the R3–R4 junction.

Finally, the TDU provides a logic-level synchronization output, which delivers a brief pulse at the beginning of each outer burst. This is useful for synchronizing external devices such as an oscilloscope.

It should be noted that the manner of connecting any external measurement instruments to the TDU should be evaluated for their impact on the overall safety of the system, for example by introducing ground faults or alternative current pathways. The TDU external connectors (power, data, electrode and monitor connectors) share a common electrical ground. Appropriate external isolation should be introduced, as needed, to ensure the safety of users and human subjects, depending on the particular experimental application. The TDU itself may be operated using its internal battery for 2–3 h, eliminating the need for external power for that period of time.

2.6. Modes of operation and external control

The TDU may be used either as a standalone device or may be controlled by an external computer, depending on the particular needs of the user. It therefore has three modes of operation selectable by top panel controls: Standalone, Remote, and Update Pattern. TDU electrotactile stimulation is defined by the active pattern, which is the set of waveform parameters defined above in Section 2.2. The active pattern may be defined in real time via software commands (below), or may be set to one of 53 pre-programmed patterns in the TDU's non-volatile memory. Only one pattern is active at any given time.

Standalone mode allows the user to control, via a top panel keypad, which of the 53 static pre-programmed patterns is displayed (i.e. made active). The side knob adjusts overall

pattern intensity (voltage). Serial communications and auxiliary analog inputs (1–5), accessible on the side panel, are disabled in standalone mode.

Remote mode enables a command interpreter in the Main microcontroller, which allows an external computer to control all TDU functions except power and mode. The command set includes functions to turn electrode stimulation on and off and control its overall level, based on the side panel knob position (which may also be disabled). It is also possible to modify all waveform parameters in real time for the active pattern (see Section 2.2), which may be either a pre-programmed pattern or a completely custom pattern. Remote mode allows the parameters of the active pattern to be sent back to the external computer. In remote mode, the top panel controls are disabled, but all the analog inputs are readable, including the one to which the side panel knob is connected.

Update pattern mode only allows pre-programmed patterns to be updated or queried via the serial port. Tactile stimulation is disabled in this mode.

3. Tongue electrodes

Although the TDU may be used (within its voltage and pulse timing limits) with any kind of stimulation electrodes, we have developed a particular geometry which is convenient and yields comfortable and controllable electrotactile sensations (Figure 2). This array, fabricated by a commercial flexible printed circuit vendor, is a 12×12 square matrix mapped to the TDU output connectors via an insulated flex circuit strip. Each of the electrodes is 1.55 mm diameter and the center–center spacing is 2.32 mm. The overall dimension of the array is therefore 27×27 mm, which fits comfortably on the tongue with the flexible strip exiting the mouth and held gently between the teeth or lips. The exposed electrodes are gold-plated surface copper pads. This gold layer, which is included to minimize electrochemical reactions at the tongue, is deposited using an "electroless" (chemical, not electrochemical) process and is very thin, and degrades with prolonged use (hundreds of hours). A thicker electroplated layer for longer life is being explored.

3.1. Electrical properties

Figure 6 shows typical measured voltage and current on one TDU electrode near the center of the array. The electrical properties of the electrode-tongue interface have not been studied in detail. Preliminary measurements show that for the above geometry, an electrode in firm but comfortable contact with the tongue presents a resistive component of approx. 1 kΩ, in series with a resistive-capacitive network of 4–6 kΩ in parallel with 0.5 nF. These values depend on electrode diameter; a larger electrode reduces resistance and increases capacitance. If the electrode does not firmly contact the tongue, the resistance may drop by several times, due to saliva becoming the primary current pathway.

The above electrode size and spacing limit the density of spatial information that may be displayed. The tactile resolution of the tongue is in the order of 0.6 mm [9], suggesting that more dense arrays might be successfully employed. However, smaller electrodes degrade the quality of the electrotactile sensation, which acquires more of a "stinging" quality as electrode size decreases [23]. Research is necessary to determine whether this tradeoff may

be at least partially mitigated by using different stimulation paradigms, e.g. by the use of depolarizing per-pulses [46].

3.2. Practical considerations

3.2.1. Threshold variations—Because electrodes at the array periphery are not fully surrounded by additional electrodes that are able to serve as return current paths, the electric potential distribution in the tongue may be different near these electrodes, compared with electrodes more centrally located on the array. This asymmetry however does not appear to result in different sensitivity to tongue stimulation at the array edge, according to unpublished pilot experiments similar to [47]. The published study showed, however, that there are gradual threshold variations across the surface of the tongue that are not localized to the edge of the electrode array. In particular, the lowest thresholds were observed anteriorly and medially (near the tip, which has the highest density of nerve endings) compared with more posterior and lateral regions. Practical applications may need to take into consideration these sensitivity differences and make appropriate compensations, as necessary.

3.2.2. Active vs. passive

The tongue may rest in a fixed position on the tongue, or may actively scan the surface, depending on the particular application. Scanning the array using the tip of the tongue affords higher resolution (due to the higher density of tactile nerve endings in the tip of the tongue) and more control over information acquisition, at the expense of a smaller "field of view", similarly to fingertip-scanned tactile displays [35]. Even if the tongue has a fixed position on the array, it may be possible for the user to indirectly control the display of information on the electrode, for example, by manipulating the camera in a tactile vision system [3].

4. Selected applications

Approximately 15 TDUs have been built and used in various collaborative research projects at the University of Wisconsin–Madison and in other laboratories in the USA, France, Canada and Mexico. The TDU has not been offered for sale commercially. Tongue-based electrotactile display, using the TDU, has been investigated for several practical applications in sensory substitution and neurorehabilitation. Over one hundred potential applications in the realm of sensory systems, communications, human–machine interfaces, and neurorehabilitation have been identified; selected applications will be detailed below.

General theory and application of electrotactile stimulation have been reviewed elsewhere [28,30,31,48–50]. Extensive reviews of tactile-based information display and sensory substitution may be found in [1–6,51]. There are additional reviews specifically concerning tactile substitution of vision [52–54], audition [55–58], from specialized sensors that monitor the status of prosthetic devices [59–61], and from teleoperators and virtual environments [62].

4.1. Vision substitution

Tactile Vision Substitution (TVS) was the initial motivation for designing the TDU. With TVS, a user-controlled video camera captures a real-time image from the ambient environment and provides a spatially-corresponding tactile stimulation to the user's skin. Based on the tactile sensation where, for example, regions of strong tactile stimulation might correspond to light areas of the camera image, users are able to perform visual tasks such as reading text, object identification and localization, hand-"eye" coordination (e.g. catching a ball), and obstacle avoidance while walking [52,63–65].

4.1.1. Tongue—*TVS* Many of these early results with TVS systems utilizing tactile displays on the abdomen or back have been replicated using tongue-based TVS [1,2]. Specific behavioral studies published include an estimation of tongue-TVS visual acuity using the TDU [66], and using the BrainPort™ Vision Device (Wicab, Inc., Middleton, WI, USA), a commercial tongue-based electrotactile sensory substitution device based on operational principles pioneered by the TDU [67]. Navigation of a human-controlled robot, while receiving visual information from a robot-mounted camera, and displayed on the tongue using the TDU, has also been reported [68]. Interestingly, the concept of tongue TVS was independently proposed in 1920 [69] and 1999 [70], but apparently never implemented until the TDU-based system.

4.1.2. TVS neuroplasticity—Visual-tactile brain plasticity, in which the visual cortex shows activity attributable to tongue-TVS use, has been demonstrated using positron electron tomography [71,72]. As also shown for blind Braille readers [73], experienced blind tongue-TVS users experience tongue tactile sensations in response to transcranial magnetic stimulation of the occipital cortex [74], indicating bi-directional plasticity between the tongue somatosensory and visual systems.

4.2. Balance substitution

Tactile substitution of balance information has been used to provide cues of head tilt for persons with disorders of the balance organs in the inner ear due to drug reactions, trauma, or conditions such as Meniere's disease. Individuals lacking any clinically-discernible vestibular function (bilateral vestibular deficit) show immediate improvement in postural stability while using a TDU, which in this case displays head tilt as the position of a small spot of electrotactile stimulation on the tongue [75]. Such improvements persist for hours to weeks and often longer, even after the device is removed from the mouth, depending on the cumulative time the subject has used the system (typical usage is two half-hour sessions per day).

This method has been commercialized as the BrainPort™ Balance Device (Wicab, Inc.), which has been extensively tested by the investigators [76] and by independent researchers [77, 78]. Earlier attempts to improve balance via non-tongue sensory substitution systems have shown immediate improvement, but no long-term beneficial effect [79,80]. Finally, TDU and TDU-like research devices have also been shown to reduce postural sway resulting from Achilles tendon vibration [81], neck extension [82] and fatigued trunk muscles [83]. In

the latter two citations, plantar pressure, rather than head tilt, was measured by a force plate and was used to control the tongue stimulus.

4.3. Induced neuroplasticity

It has recently been shown that the presumed *neuroplastic changes* responsible for the long-term benefits of TDU-based vestibular substitution may be realized *without* the informational component. TDU or TDU-like tongue stimulation delivered simultaneously with balance and gait exercises, even if the tongue stimulus is not linked to head, plantar or any other kinds of sensor, appears to yield both long-term symptom reduction as well as measureable changes in brain activity [84–90,100,101]. This new method, which is not sensory substitution, but which may, if desired, be combined with sensory substitution, has been dubbed Cranial-Nerve Non-Invasive Neuromodulation (CN-NINM) and is under investigation at the Tactile Communication and Neurorehabilitation Lab (TCNL) at the University of Wisconsin–Madison.

4.4. Augmentative information display

Coded tongue-tactile signals have also been proposed and demonstrated to enhance situational awareness, mobility and dexterity for persons engaged in delicate, high-risk, covert, and/or visually-obstructed tasks [1,91–93]. For example, guidance of a surgical tool manipulation has been demonstrated using only TDU-based feedback [94], and tactile feedback from robots to assist spinal cord injuries has been proposed [95], along with tactile feedback of seated pressure, to prevent pressure sores [96] and to gain greater awareness of ankle joint rotation in a fatigued state [97]. The TDU as a platform technology allows virtually any kind of information to be presented to the tongue, subject to the human limits of electrotactile perception on the tongue, which are just beginning to be explored [98].

5. Disclosure

Tongue-tactile-display technology is patented in the USA and other countries by the Wisconsin Alumni Research Foundation [99], from which the author receives royalty payments. The author also has an ownership interest in Advanced NeuroRehabilitation, LLC (Madison, WI, USA), a company formed to develop and commercialize non-invasive neuromodulation technology. The TDU itself has not been commercialized.

Acknowledgments

Biography

Kurt Alan Kaczmarek (M'86-SM'05) received a B.S. degree from the University of Illinois, Urbana, in 1982, and M.S. and Ph.D. degrees from the University of Wisconsin–Madison, Madison, in 1984 and 1991, respectively, all in Electrical Engineering. From 1984 to 1986, he was Senior Engineer with Baxter International, Deerfield, IL. He is currently Senior Scientist at the University of Wisconsin, Madison, where, since 1992, he has been studying the mechanisms and perception of electrical stimulation of touch. His current research interests include tactile displays, sensory rehabilitation and augmentation, teleoperation and neurorehabilitation.

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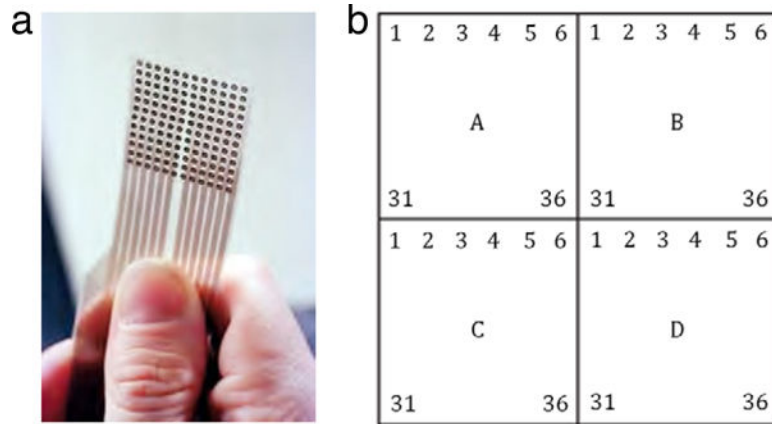
(a) Tongue display unit.

(b) Electrode array.

Figure 1.
Photo of tongue display unit (a) and electrode array (b). Jeff Miller, University of Wisconsin–Madison, used with permission.
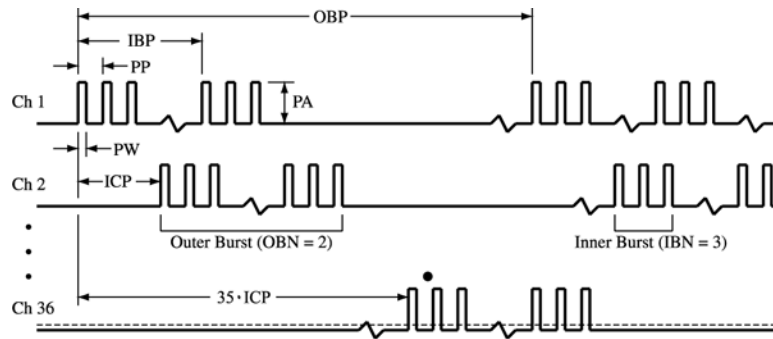
Figure 2.
The TDU electrode array (a) is divided into four 36-electrode blocks (A–D), each of which is raster-scanned in synchrony with the other blocks (see text). The bottom of the array in this figure rests approximately 1 cm posteriorly to the tip of the tongue. Jeff Miller, University of Wisconsin–Madison, used with permission.
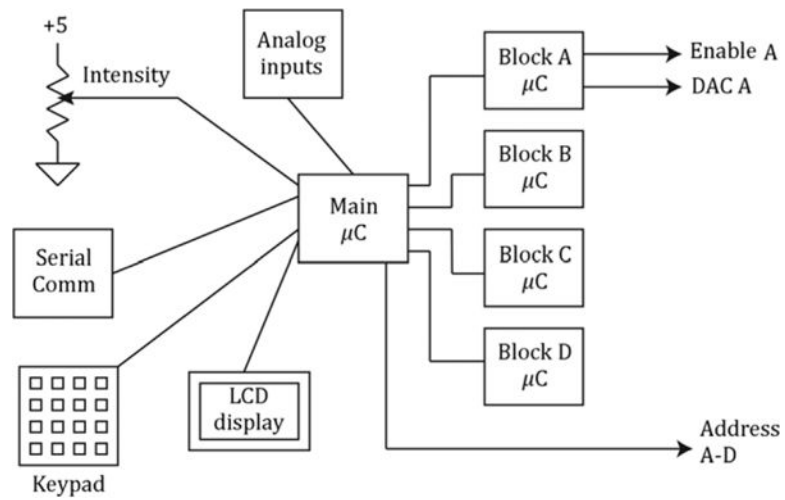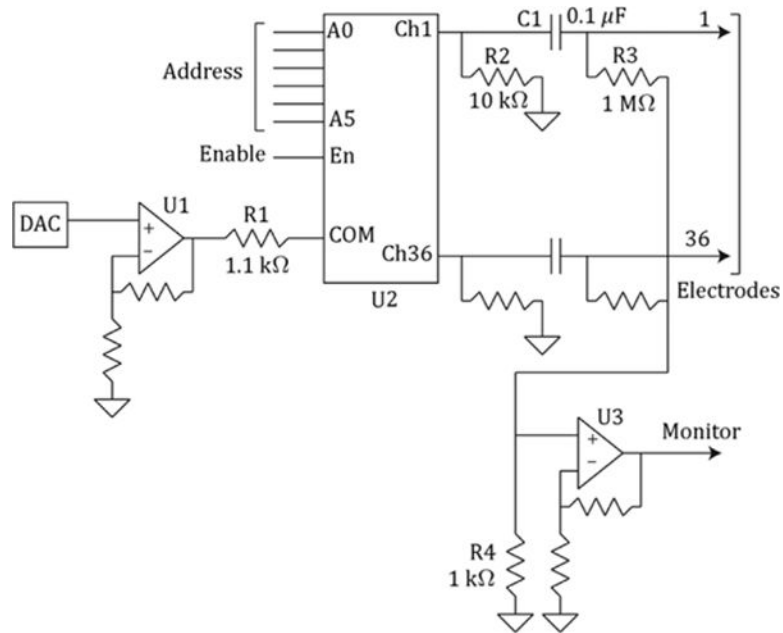
Figure 3.
Block diagram of TDU. The main microcontroller (μC) accepts control inputs from an intensity control, keypad and RS-232 serial port. It controls the four block (A–D) microcontrollers, each of which controls pulse timing for one block via the output circuit shown in Figure 5. An LCD display provides status information to the user.
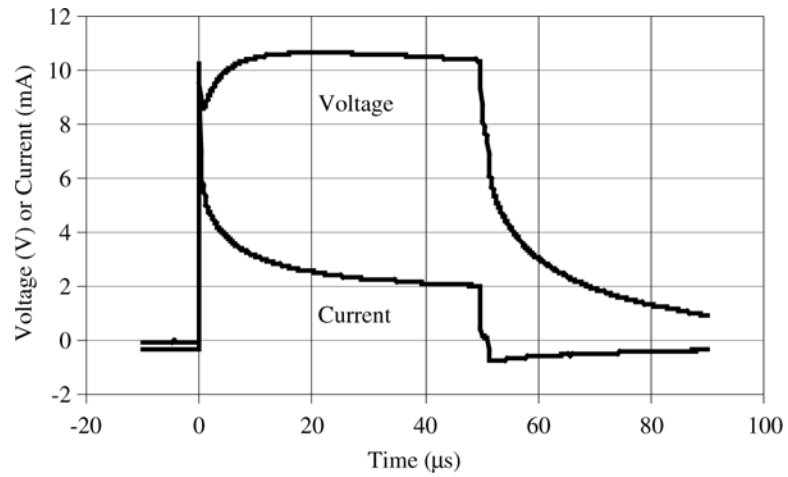
Figure 4.

The TDU output waveform includes multiple levels of pulse grouping to achieve the desired tactile sensations (see text). Pulses are grouped into inner bursts, which are further grouped into outer bursts. Pulse amplitude, burst timing, and numerosity are controlled by the following parameters: Outer Burst Period (OBP), Inner Burst Period (IBP), Pulse Period (PP), Pulse Width (PW), Outer Burst Number (OBN), Inner Burst Number (IBN), Inner-Channel Period (ICP), Pulse Width (PW) and Pulse Amplitude (PA). Table 1 defines the operational range for these parameters.

Figure 5.
The TDU output circuit (one block shown) contains circuitry to control pulse amplitude (DAC and U1), active output resistance (R1), passive output resistance (R2), dc suppression (C1), dc stabilization (R3), and external monitoring (R3, R4, U3); see text. The analog multiplexer U2 controls pulse timing according to logic pulses on the address and enable lines; these signals are produced by the microcontroller for each block (Figure 3).

Figure 6.
Typical TDU measured waveform. Captured using a Tektronix A6312 current probe and AM503B current probe amplifier, and an Agilent DSO6034A digital oscilloscope. Spike at beginning of waveform is current trace due to electrode-tongue interface capacitive component (see text). The electrode array in Figure 2 was used; electrode diameter is 1.55 mm.

Table 1

TDU stimulation parameters. Parameter values are controllable in real time, updated at the beginning of each outer burst, within the limits shown in the table.

Symbol	Name	Range	Resolution	Units	Typical range	Standard waveform
PA	Pulse amplitude	0–40	0.157	V	5–20	Varies per user
PW	Pulse width	0–510	2	μs	10–100	50
IBN	Inner burst number	0–255	1	pulses	1–10	1
OBN	Outer burst number	0–255	1	bursts	1–10	3
PP	Pulse period	2–510	2	μs	10–100	n/a
IBP	Inner burst period	0–25.5	0.1	ms	1–10	5
OBP	Outer burst period	5–1,275	5	ms	10–1000	20
ICP	Inner-channel period	2–510	2	μs		138

The following additional restrictions ensure the integrity of the burst structure:

PW < PP

PP·IBN < ICP

ICP·35 < IBP

OBN·IBP < OBP.