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BrainPort® Technology Tongue Interface Characterization

Wicab, Inc.
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MARCH 2010
Final Report

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14. ABSTRACT

Wicab, Inc. has developed novel technology which allows information from external devices to be sensed by humans via neuro-stimulation of the tongue.

This report summarizes a multi-year effort to empirically measure the electro-stimulation properties of the tongue, including spatial and temporal discrimination, contrast sensitivity, and stimulation optimization approaches.

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1   PROJECT SUMMARY

Wicab, Inc. has developed novel technology which allows information from external devices to be sensed by humans via neuro-stimulation of the tongue. Applications are numerous and include the BrainPort® balance device to assist patients with vestibular deficits, the BrainPort vision device, a sensory augmentation device for the blind, and the BrainPort Underwater Sensory Substitution System which provides navigational cues to military divers. Current devices present data to the tongue using low density electrode arrays (100-625 elements, ~6.45cm^2).   Present and future applications may benefit from array densities and electro-stimulation waveform patterns that match the spatial/temporal resolution of the tongue.   Therefore, characterization of this resolution is the key to full exploitation of the tongue sensory channel.

This DARPA-funded research program is a multi-year effort to empirically measure the electro-stimulation properties of the tongue. Advanced hardware devices and associated software were developed to support experimental protocols. Under this Program   approximately 60 subjects and more than 200 subject hours were involved in the following experiments:

- Two-point discrimination
- Temporal gap detection
- Tongue mapping
- Spatial summation
- Contrast sensitivity
- Neuro-stimulation optimization
- Percept Training - Sharpshooter simulation

All experiments involving human subjects were conducted under an IRB approved protocol.

The Program's objective was to provide empirical evidence concerning the psychophysical limits of the tongue in order to characterize its information capacity.
Prior to this program-

- Little was known regarding the psychophysical limits of tongue electro-stimulation

- Minimum electrode size and aggregate electrode density limits for tongue stimulation were guesses, at best

- It was unknown whether electrode arrays with sub-millimeter diameter electrodes and associated circuitry could be could be fabricated and safely driven such that sufficient charge reaches the tongue's receptors to allow detection (i.e. would the minute charge find return paths before reaching the depth of the receptors)

- It was unknown whether a human subject could detect electrical stimulation pulses on the tongue presented via electrodes in the sub-millimeter diameter range

The results of this program clearly demonstrate that the human tongue is capable of temporal/spatial detection of electrical signals at least equal to, or better than, other electro-tactilely sensitive locations (fingertips, for example) and that electro-stimulating arrays with

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electrode diameters and spacing of less than 250 microns can present useful information. The results also demonstrate that there are individual variations in task performance. Test subjects were not chosen for their tongue perception ability, so —super-performers" which would improve the threshold limit may have not have been tested.

While this suite of studies provides empirical data regarding the psychophysical characteristics of the tongue, they should not be interpreted as the absolute limits. The results from these experiments begin to characterize the information channel, but they do not represent the true limits of the channel. In order to assess the absolute limit, four experimental components need to be optimized: subjects, training, application, and technology. This was beyond the scope of the current program.

1.1   Significant Findings

- **Electro-tactile psychophysical characteristics of the tongue**
  Two Point Spatial Discrimination is 0.75mm on average, with some individuals able to detect 0.25mm or better.   This implies that arrays on the order of 0.125mm center-center electrode spacing (or better) may be useful for high performing individuals.

  Temporal Discrimination is on average 75ms, with some individuals performing at 50ms or better gap detection. This implies that array frame rates of 20 Hz or faster should be useful for high performing individuals.

  Test data suggests that tongue sensitivity is a function of stimulation location as well as number of stimulating tactors. In addition, the dynamic range in voltage (stimulation intensity) is a function of the number of stimulating tactors. This data may have implications on the electro-mechanical design of high density arrays, as well as the stimulation waveform and power requirements.

  Preliminary data from static 2-D grating tests indicates that average spatial discrimination is 0.6mm (compared to 0.75mm for 2pt tests). This implies that there may be strategies to further improve the average spatial discrimination ability.

  Spatial acuity and temporal acuity appear to differ within individuals - high performers in one modality are not necessarily high performers in another. This presents opportunities to train individuals whose physiology allows peak performance across modalities, to tailor information to individual performance, and to tailor arrays for specific applications.

  Finally, data from this study confirms that electro-neurostimulation of tongue is on par with other stimulation modalities: mechanical grating ~0.500mm (Van Boven, 1994) and vibro-tactile at ~20Hz (Ezawa, 1988).

  Note that for these studies, subjects did not receive extensive practice with the stimuli, which may extend the psychophysical limits. Also, researchers found that task demands affect the reported threshold. For example, two point discrimination was ~0.75mm but

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spatial gratings threshold was closer to ~0.5mm. Therefore, to define the absolute threshold, either the task needs to be fixed to a task of interest or there needs to be converging evidence from a variety of experiments testing similar skills. Finally, subject performance is only as precise as the equipment being used. To report a definite threshold, additional instrumentation suitable for this unique environment is necessary.

- **High Density Array Design and Experiment Control**
  Experimental data indicates 0.125mm electrode spacing (200/inch) should match the tongue's spatial acuity. Using a simple fabrication technique, arrays with 0.152mm spacing (Figure 1) were assembled (densities beyond this level requires a significant technology investment). These near-optimal arrays allow advanced testing of dynamic information on the tongue.
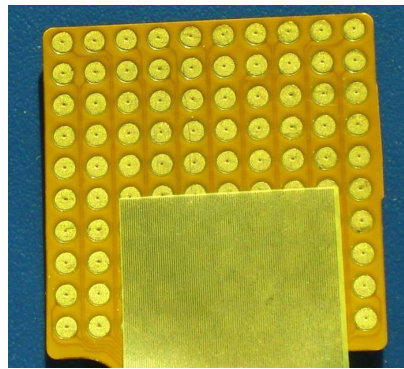
Figure 1. Original Electrode Array (10 electrodes/row) and High Density Strip Array (100 electrodes)

An electrical control system was designed and implemented which allows concurrent control of all electrodes in an array. This system manages the safe delivery of stimulation to any number of simultaneous electrodes, as well as manipulation of the return path geometry. In addition, stimulation waveform patterns can be defined for evaluation of waveform on spatial and temporal detection properties. The system is designed to manage up to 27,000 electrodes, although for practical testing, we have limited the current implementation to 2000 element arrays.

An experimental control software application was developed to allow researchers to define experiments using any configuration of electrode geometry and stimulation waveform patterns. Experiment sessions are defined and executed to present stimulus information to subjects and record their responses. All data is archived for off-line analysis.

- **Neuro-stimulation Optimization**
  Hardware and software were developed to allow exploration of pulse frequency and affects on spatial summation and discrimination. Data from this study supports the conclusion that dynamic range is clearly affected by neighboring stimulation pulses.

- **Stimulation Detection Strategies**

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Preliminary exploration of this area indicated that individual instruction with an experienced trainer has a more significant affect on perceptual performance than does any specific individual detection strategy. That is, individuals could be trained to achieve the same level of performance for a given task regardless of how they used their tongue to feel the stimulation. Effort under this task was combined with the ‗Enhanced Percept' task and others, to focus on instruction and training development.

- **Enhanced Percept – Rifleman Training**
  Subjects were trained to hold a rifle (Figure 2) with 0 degrees of cant and were either given verbal training or automated training with feedback from an integrated BrainPort-based tongue display. Both groups achieved skills at holding the rifle in a stationary vertical orientation and performance improved with training. There is no clear difference between subjects trained by human interaction or those trained exclusively with electro-tactual stimulation.

  These results suggest that providing electro-tactile information to the tongue is an effective alternative method for providing rifle position training to a novice.   As a result, training techniques could be modified to incorporate aspects of automated training, thus directing human interaction coaching to other aspects of rifle skill acquisition.

Figure 2. Modified Mock Weapon for Rifleman Training

1.2 Program Information

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2   STUDIES AND RESULTS

2.1   Two-Point Discrimination

Two-point discrimination was performed using a modified BrainPort Balance Device C200 (BBD-C200). Nine linear arrays with ten electrodes each were produced with industry standard printed wiring board technology. The individual electrodes ranged in diameter from 1.5mm to 0.169mm and were spaced (center to center) at a distance of 1.5 times the electrode diameter. The smallest electrode size and spacing represents the highest resolution readily available from commercial printed wiring board vendors. Sufficient arrays were produced so that each test subject used a new array, minimizing the effects of electrode corrosion and resultant changes in impedance.

The stimulus generation circuit employed in the BBD-C200 consists of a ColdFire 32-bit microcontroller, Texas Instruments digital to analog converter (TLV5630), Burr-Brown operational amplifier (OPA4132), and a bank of Analog Devices demultiplexers (ADG408BRU) used for routing the stimulus signal to any one of one hundred electrode addresses. Each output of the demultiplexers are connected to an AC coupling capacitor (0.1μF ceramic) with the opposite side of that capacitor connected to the tongue placed electrode.

Internal pilot studies suggested that some subjects could discriminate two stimuli spaced 0.5mm apart. As a result, we selected a linear electrode array with 10 electrodes, each 169 micrometers (μ) diameter and spaced 254μ apart (center to center) for the formal two point discrimination experiment. This array enabled conditions that could both exceed performance and also be within the range of successful performance. Each active electrode presented a continuously repeating stimulation waveform. The waveform scheme consisted of six double stimulating pulses (21.4μsec each separated by 5μsec) repeating at 369Hz. After every 6 pulses, 2 pulses were presented at 0V (total period of waveform was 21.68ms). When two electrodes were presented, the first electrode fired 51.6μsec after the second electrode. Pulse amplitude was fixed per subject. Each subject set their own comfortable working amplitude up to 24.5V prior to the experiment, providing comfortable stimulation. This waveform scheme was selected because sensation was perceived as a comfortable and continuous stimulation.

Sixteen subjects (10 men; 6 women) participated, ranging in age from 18-39 years (mean 24.5yrs). Experiment duration was approximately two hours. Subjects were recruited from the Madison, WI area. All subjects gave informed consent with a study protocol approved by the New England IRB. Pulse amplitude (in volts) was determined individually before running the two point discrimination experiment. Subjects were presented with trials containing one or two electrodes firing on an array. They were instructed to manipulate a hand held slider control, allowing each subject to explore and adjust the stimulation to a comfortable working level. Once a comfortable level was reached, subjects indicated their response by pressing a button on the hand-held control. ―Working level" was defined as a stimulation level that was strong and comfortable for at least five seconds. Intensity values (voltage) were gathered for one and two contiguous firing electrodes. Each measurement was repeated several times across multiple electrode locations. For each subject, the mean ―working level" for one and two contiguous points was used as the fixed voltage intensity for the two point discrimination test. These values ranged from 18-25V across participants (mean 21.46V).

Trials were presented in five experimental runs, blocked by the separation between two electrodes. These conditions were: 0.254mm (no gap), 0.580mm (1 electrode gap), 0.762mm (2 electrode gap), 1.016mm (3 electrode gap) and 1.261mm (4 electrode gap). In each block, half of the trials contained only one stimulating electrode, while the other half contained two firing electrodes of the fixed condition distance. The order of the five experimental blocks was pseudo-randomized for each subject.

Subjects were instructed to press one button on the hand-held control if they felt one stimulus on their tongue and a different button if they felt two stimuli on their tongue. They were encouraged to use the tip of their tongue (or any other part of the tongue) to search for and/or to explore the stimulation in order to respond maximally. There was no response time limit. In this way, subjects could explore the stimulus with whatever part of the tongue they felt gave them the best information.

To familiarize subjects with electrotactile stimulation and the procedures, subjects were given 5-10 minutes of interactive practice trials. Participants sampled a few trials of each of the conditions, becoming acquainted with the trial types. During this practice phase, the researcher labeled the conditions as being truly two points or one. Subjects were told there may be trials where they may not be able to confidently give a correct response. They were reassured that this was necessary in order to get to the limit of spatial resolution on the tongue. During experimental testing, performance feedback was not provided.

The primary endpoint will be a threshold defined by a group d-prime greater than or equal to one (by subject and by group), indicating subjects are sensitive to the presence of two categories (CBASEE 1985). Calculating d-prime (d'), a measure of sensitivity in a discrimination task, is computed by the standardized difference between the false alarm rate and the hit rate: $d'=z(H)-z(FA)$ (Macmillan & Creelman 2005). The hit rate is the proportion of correctly identified trials of two points, when two points were actually stimulated. The false alarm rate is the proportion of incorrect trials where the subject reported two points, but only one point was actually stimulated. The numeric output of d-prime represents the perceived distance between the two categories. A d-prime near zero represents chance discrimination, where subjects are insensitive to the condition categories. When d-prime is greater than one, at least one standard deviation separates the two response categories indicating that subjects are sensitive to and correctly responding to the condition categories.

As a secondary endpoint, individual d-prime measures by condition were statistically explored post-hoc using a one way ANOVA. Individual differences were further explored by computing the percentage of subjects whose individual performance exceeded d-prime discrimination greater than one. Figure 3 illustrates performance across participants.

Two Point Discrimination
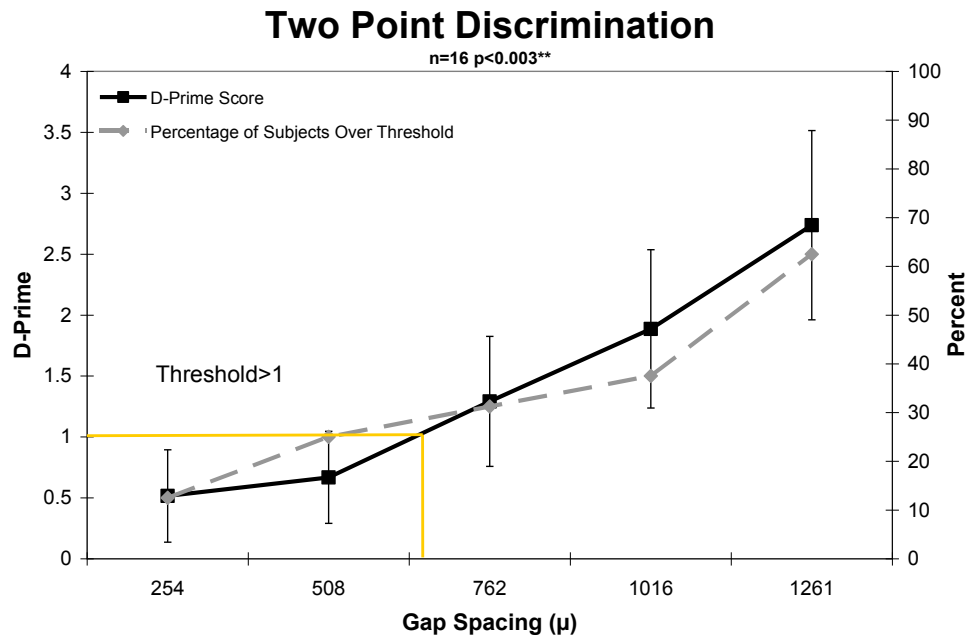
Figure 3. Two Point Discrimination Across Participants

The line graph (left y-axis) represents the group's mean d-prime performance across the five electrode spacing conditions. As a group, performance exceeded d-prime>1 when electrodes were spaced 0.762mm (2 electrode gap). A one way ANOVA revealed a significant main effect for electrode spacing ($F_{(4,60)}=4.466$, $p<.005$). As the electrode spacing increased, performance improved. The line graph (right axis) illustrates the percentage of subjects in each condition who individually exceeded threshold. For example, 12.5% of subjects scored above threshold in the most closely spaced 254μ condition. So while the group average threshold is 0.762mm, there are individuals who have better than average discrimination abilities. This may suggest that an individual's actual limit may be better than 0.254mm spacing.

2.2 Temporal GAP Discrimination

Gap discrimination was performed using a modified BrainPort Balance Device C200 (BBD-C200) as described above. Internal pilot studies suggested temporal gaps with the smallest array (0.254mm spacing) were difficult to discriminate. Using a linear array with 10 electrodes sized 0.667mm spaced 1.0mm apart, internal subjects were able to feel temporal gaps of 50-100ms in duration. With this array, conditions were generated that could both exceed performance and also be within the range of successful performance. All gap discrimination conditions use a continuous repeating pulse scheme presenting 1 pulse for 25μs wide every 125μs (frame) to each electrode with a programmable ―gap" of no stimulation on one of the electrodes. For the ―gap" condition, the electrode pulses for a total of 500ms (four frames) followed by an ―off gap" of 33-250ms.

Sixteen subjects (10 men; 6 women) participated, ranging in age from 18-39 years (mean 24.5yrs). Experiment duration was approximately two hours. Subjects were recruited from the Madison, WI area. All subjects gave informed consent with a study protocol approved by the New England IRB. Some, but not all, subjects participated in the 2-pt Discrimination Test. Pulse amplitude (in volts) was

determined individually before running the gap discrimination experiment. Subjects were presented with trials containing electrodes firing on the array with variable gaps in the continuous stimulation. They were instructed to manipulate a hand held slider control, allowing each subject to explore and adjust the stimulation to a comfortable working level. Once a comfortable level was reached, subjects indicated their response, using either a thumb or finger to press a button on the hand-held control. "Working level" was defined as a stimulation level that was strong and comfortable for at least five seconds. Intensity values (voltage) were repeated several times and averaged across conditions, creating a mean "working level" as the fixed voltage intensity for the gap discrimination test.

This experiment consisted of five blocks of experimental runs containing twenty Two-Alternative Forced Choice (2AFC) trials for a total of 100 trials. Each trial contained two stimulating electrodes, one on the right and one on the left, spaced four electrodes apart. For every trial, one electrode was continuously firing (as defined above), while the other electrode had a temporal gap. The targeted gap stimulus was presented "on" for 500ms followed by one of five "off" gaps: 33ms, 50ms, 75ms, 100ms and 250ms. This target stimulus cycled through "on" and "off" continuously while the other electrode presented a continuous waveform. The two stimuli were presented until the participant indicated which stimulating electrode had the temporal gap.

Subjects were instructed to press the left button if they felt the stimulus had a temporal gap on the left, else, press the right button if they felt it on the right. Half the correct responses for the trials for each were presented on the right and left respectively. Again, the participant was allowed to take as much time as needed and a free moving tongue was allowed. In this way, subjects could explore the stimulus with whatever part of the tongue they felt gave them the best information. The order of the five blocks was pseudo-randomized for each subject and there was no performance feedback given. Two point discrimination performances translated into a percent correct score for each temporal gap and subject. Effective discrimination threshold was defined as when the percent correct was greater than 75%. Figure 4 illustrates performance across participants.
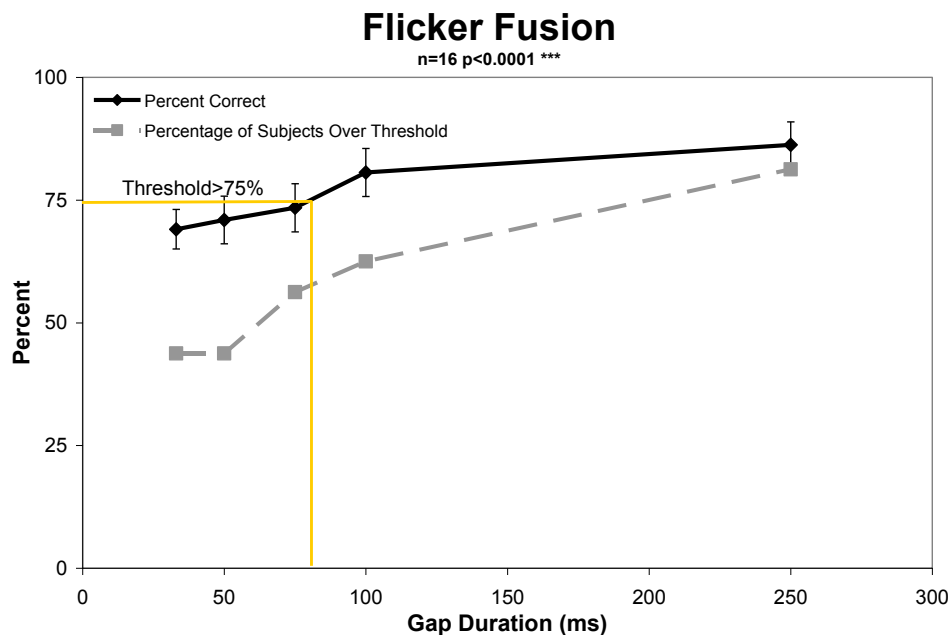
Figure 4. Gap Detection Across Participants

The line graph (left y-axis) represents the group's mean d-prime performance across the five temporal gap conditions. As a group, performance exceeded d-prime>1 when electrodes had a gap of at least 75ms. A one way ANOVA revealed a significant main effect for electrode spacing ($F_{(4,60)}=6.239$, $p<.005$). As the temporal gap increased, performance improved. The dotted line illustrates the percentage of subjects in each condition who individually exceeded threshold. While the group average threshold is 75ms for gap detection, there are individuals who have better than average discrimination abilities. This may suggest that an individual's actual limit may be better than 50ms.

2.3   Tongue Mapping & Spatial Summation

A review and analysis of the tongue mapping and spatial summation data using the 25x25 tongue array suggests tongue sensitivity is a function of stimulation location as well as number of stimulating electrodes. A representative three-dimensional tongue sensitivity map is included (*Figure 5*). The front center of the tongue has the greatest sensitivity, as indicated by the lowest voltage region. As stimulation is placed near the back of the tongue, the mean sensitivity is decreased. When many electrodes are stimulated, less voltage is required for threshold and working levels. When one electrode is stimulated, more voltage is required for threshold and working levels. The spatial summation graph, Figure 6, illustrates that sensitivity is a function of the size of the stimulating area on the tongue. In addition, the graph illustrates the dynamic range in voltage as a function of the number of stimulating electrodes, where there is a greater range when one electrode is firing as compared to a smaller range when nine electrodes are firing.
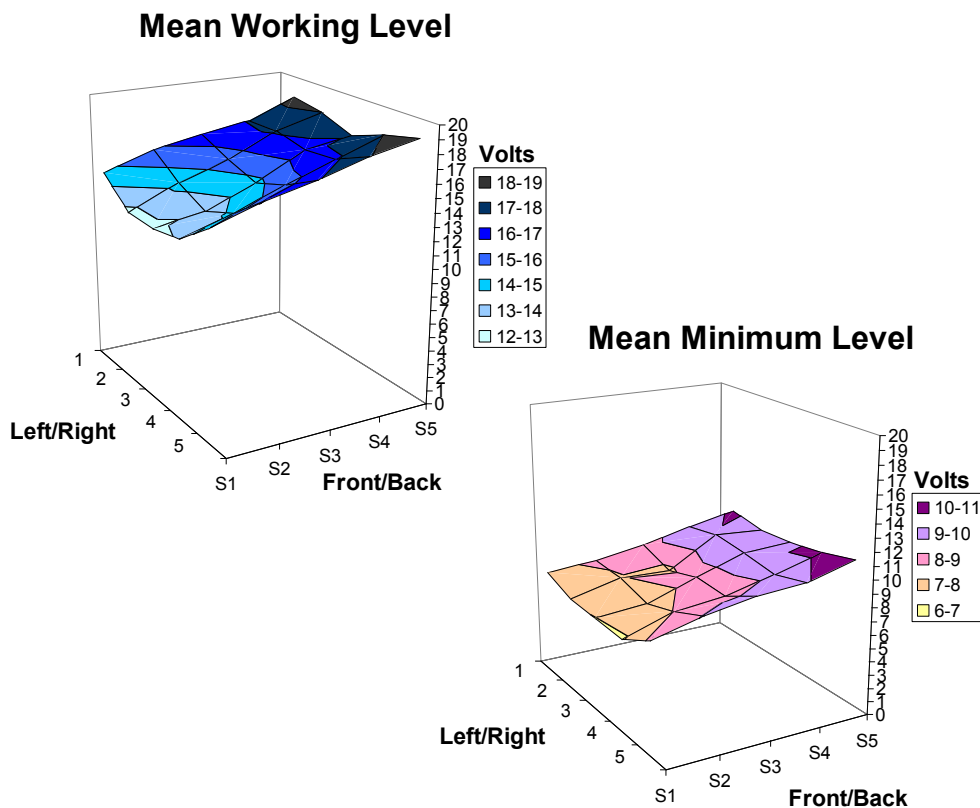
Figure 5. Tongue Sensitivity Maps
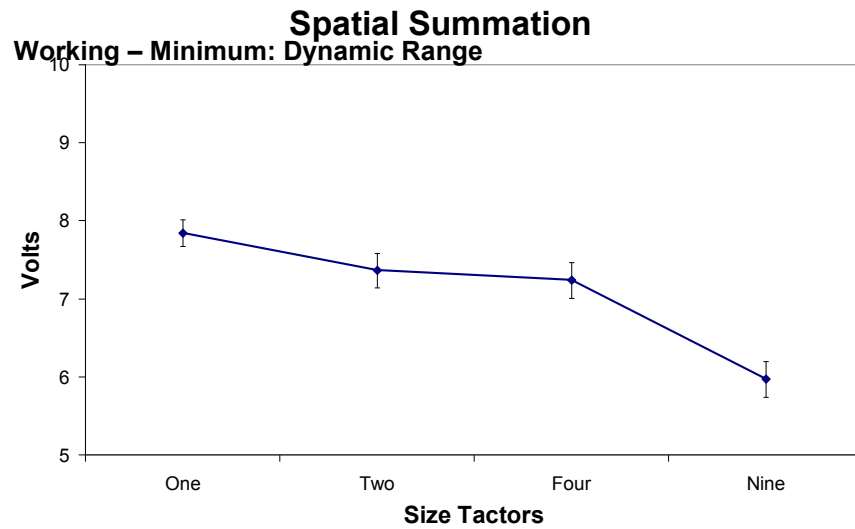
Figure 6. Spatial Summation

2.4   Contrast Sensitivity

Using the 20x20 portion of the High Density TUNS array (76μm diameter electrode, 152μm center-to-center spacing), contrast sensitivity was measured in five participants. Twenty-five experimental blocks included five trials each of five spatial line gratings presented at five different contrast levels:

5-gap (760μm)	100% Working Level Voltage
4-gap (608μm)	80% Working Level Voltage
3-gap (456μm)	60% Working Level Voltage
2-gap (304μm)	40% Working Level Voltage
1-gap (152μm)	20% Working Level Voltage

Figure 7 illustrates the general experimental design (not to scale).
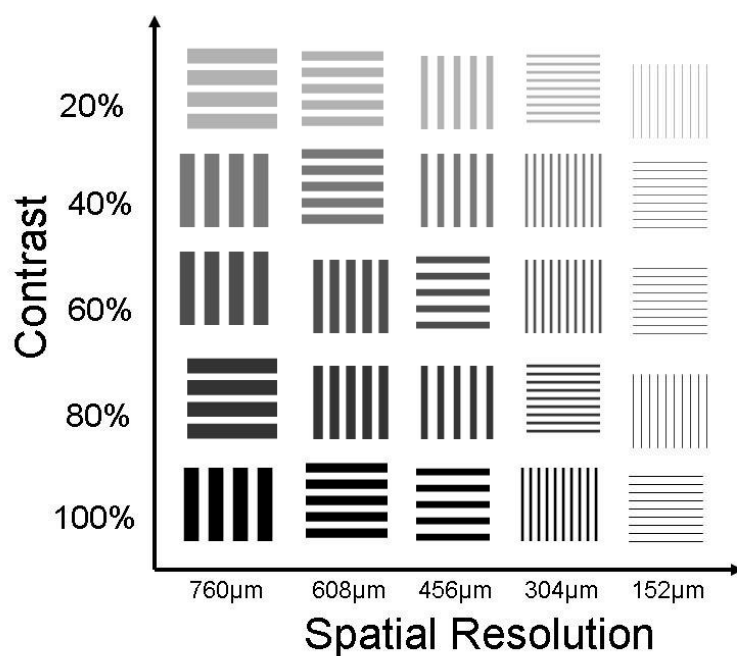
Figure 7. Contrast Sensitivity Experiment Design

Each experimental block consists of 15 randomly presented grating orientations: 5 horizontal, 5 vertical or 5 neither (diagonal). Participants were required to make a Three-Alternative Forced Choice indicating the direction of the presented grating. Perceptual threshold is reached in conditions where percent correct exceeds 66.67%.

A two-way ANOVA (gap-spacing x contrast) was performed, resulting in a significant main effect of gap spacing, Figure 8, $(F_{(4,16)}=6.044, p<.004)$, a significant main effect of contrast level, Figure 9, $(F_{(4,16)}=5.406, p<.006)$, with no significant interaction.

Main Effect of Gap Spacing*
n=5 p<.004
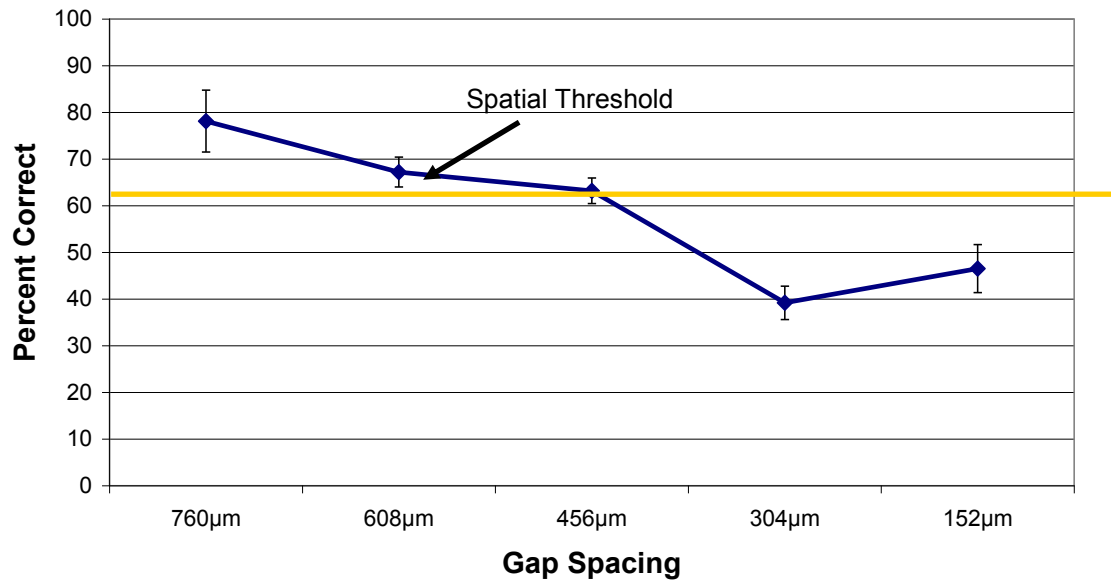
Figure 8. Main Effect - Gap Spacing

Main Effect of Contrast Voltage*
n=5 p<.006
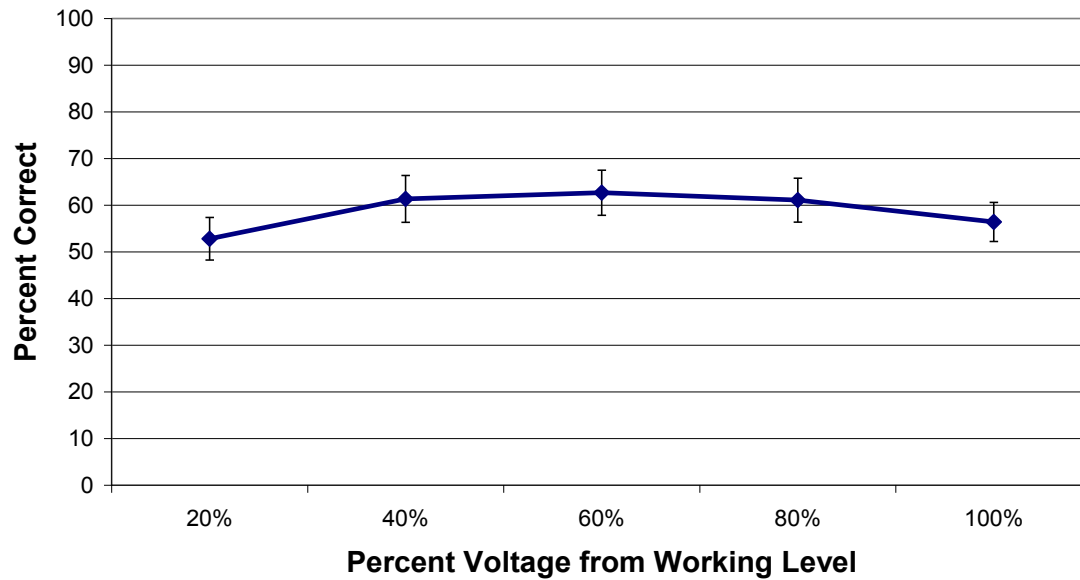
Figure 9. Main Effect - Contrast Voltage

Group percent correct values for each experimental condition are shown in the following table. Conditions that meet exceed threshold are highlighted in yellow.

	760µm	608µm	456µm	304µm	152µm
20%	74.67	57.33	54.67	37.33	40
40%	84	74.67	57.33	37.33	53.33
60%	84	64	68	38.67	58.67
80%	82.67	72	66.67	40	44
100%	65.33	68	69.33	42.67	36.67

Using this data, a graphical ―Contrast Sensitivity" chart is included, Figure 10, (not to scale), with conditions that meet or exceed threshold are highlighted in yellow. Two conditions, colored in light green (100%/760um, 60%,608um), are close to threshold and one would assume with more subjects would be included as above threshold.
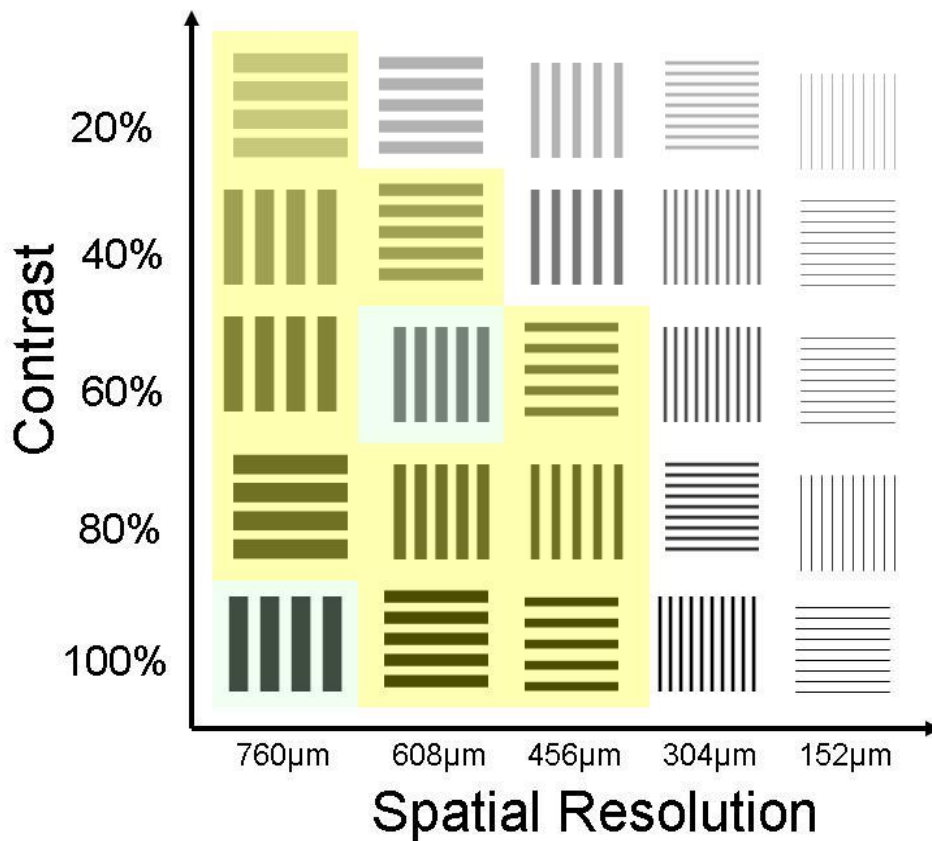
Figure 10. Contrast Sensitivity Chart

2.5   Aggregate Channel Capacity

Upon building two-dimensional high density arrays, we explored and evaluated the tongue's capacity to interpret information with both spatial and temporal components. One specific goal was to test motion perception on the tongue. Exploration included determining interaction between stimulation size, movement velocity and frame rate on perceptual discrimination. In addition, we explored the ability of the tongue to detect linear discontinuities (Vernier Acuity) to discriminate small features.

Motion Perception

Motion perception on the tongue was initially explored using our 25x25 vision arrays (1mm center-to-center spacing), with points of varying sizes. Regardless of size, directional information was easy to perceive. Moreover, we could not find a combination of size/speed that we felt was challenging enough to explore the limits of this perception. We next explored this same task using the high-density 20x20 array, which notably covers a much smaller portion of the tongue. As a result, we found that moving balls across this small area became too difficult to perceive the direction of motion. Most users were able to perceive orientation, but the motion did not cover enough space to form an accurate perception of direction. Similar issues occurred when exploring lines and gratings with motion.   Due to the limited ―workspace" of the 20x20 array, moving lines and bars appeared to fluctuate or were perceived as a repeating pulse on the user's tongue rather than the intended fluid movement.

Applied Spatial Resolution: Vernier Acuity

Six subjects participated in this experiment based upon the classic Vernier visual acuity test, using the high-density 20x20 array, where theoretically the spacing between individual electrodes exceeds the previously found spatial resolution threshold. Horizontal lines were presented and subjects were asked whether they felt a straight continuous horizontal line, or one with a discontinuity. The experiment consisted of five blocks of randomly presented trials ranging from 1-5 electrode offsets as compared to a continuous straight line:

1. 6 straight lines versus 6 lines with one electrode shift off
2. 6 straight lines versus 6 lines with two electrode shift off
3. 6 straight lines versus 6 lines with three electrode shift off
4. 6 straight lines versus 6 lines with four electrode shift off
5. 6 straight lines versus 6 lines with five electrode shift off

We predicted that subjects would not be able to reliably discriminate (d-prime >1) straight lines from shifted lines with a 1-2 electrode shift, as this would represent spatial distances smaller than our previous two-point discrimination threshold.

All subjects reported that their overall impression was that the lines were continuous and straight. As a group, when electrode shift is limited to 1-2 electrode offset, subjects were not able to detect the linear offset. Moreover, the variability as seen by the standard error bars are quite small indicating that offsets larger than our assembly error do not affect our proposed experiments. In general, when the offsets were larger, group performance improved, however there was more inter-subject variability as seen by the larger error bars. This may be due to individual differences or due to the few trials executed in this brief experiment.

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Group data is graphically presented below (Figure 11).
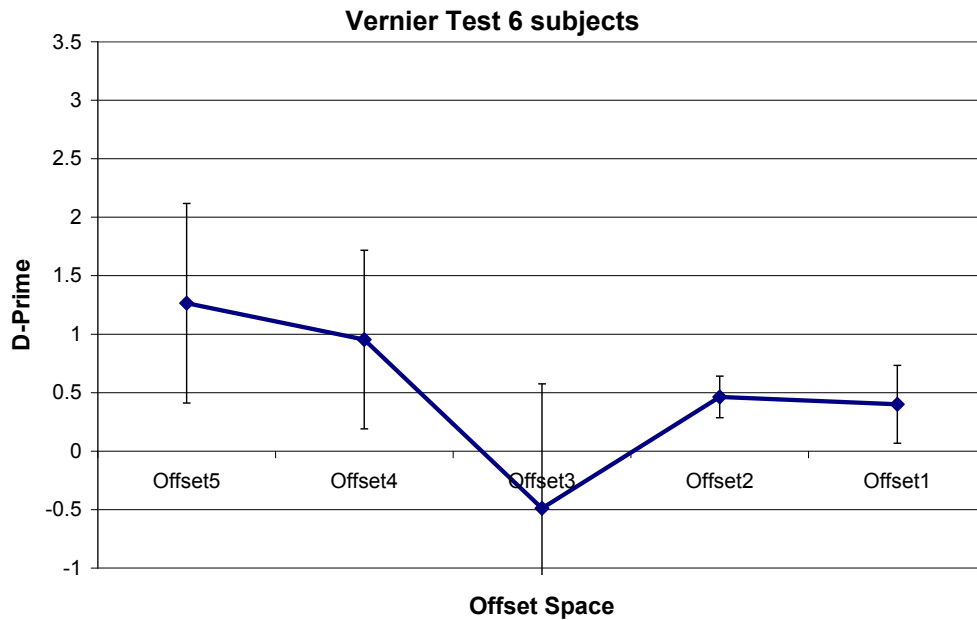
Figure 11. Vernier Test

Conclusions

Given d-prime>1 as our threshold, it is clear that for these six subjects, no offset discrimination was felt for 1-2 electrode offsets, especially given the tight standard error bars. These results confirm our earlier expectations that minor geometric errors will have little or no impact on our proposed experiments which focus on gross direction and speed of movement (up/down/left/right). Based upon strategy feedback, the best performing subject was able to discriminate the conditions by angular offset rather than discontinuity. For future reference, it appears that the tongue may be capable of small spatial angular discrimination, which may be important for some applications and experiments.

Neuro-stimulation optimization

Three subjects participated in a study evaluating dynamic range mapping of the tongue as a function of scan pattern. Historically, a progressive scanning method has been used due to equipment constraints. Changes to hardware and software design now provide the ability to modify the electrode activation sequence, within certain safety and timing constraints.

Researchers hypothesized that the progressive scan pattern may inadvertently be inducing spatial summation, where contiguous electrodes firing together feel stronger than those firing individually. Therefore, by separating the electrode firing temporally, perception may improve. However, it is unknown whether the microsecond time-frame scan patterns (beyond known temporal gap perception on the tongue) in this experiment will alter perception.

In this experiment, 4 electrode stimuli (2x2 arrangement) were presented randomly across 25 regions across the tongue, using the V100 electrode array (20x20 electrodes, 1.2 mm spacing). Subjects selected a minimum perception threshold and a maximum working level threshold, defining the dynamic range. The system allowed a maximum of 19.5 volts mapped into 100 levels. Four scan patterns were used:

Progressive — Electrodes are sequentially addressed and activated in a raster scan pattern. There is approximately 60 microseconds between adjacent electrode firing. The adjacently firing electrodes are separated by 1.2mm

Random — All electrodes are randomly sequenced for addressing and activation. A simple pseudo-random ordering is predefined, and once defined is used during all sessions (ie the random sequence of firing is not computed for each frame or run). The time between adjacent electrode firings is between 60 microseconds and approximately 5.8 milliseconds. Adjacently firing electrodes are separated by 1.2mm to 24mm

Interleave A — A predefined electrode addressing sequence is generated whereby the array is raster-scanned, but two electrodes are skipped over between sequential firings. Therefore, adjacent electrodes will have at least 360 microseconds between firings. Sequentially firing electrodes are separated by at least 3.6 mm

Interleave B — A predefined electrode addressing sequence is generated so that there is at between 2.4mm and 6mm between sequentially firing electrodes and at least 300 microseconds between adjacent firings.

In any case, all electrodes are activated within about 6 milliseconds.

In terms of minimum threshold perception, there were no significant differences between the scan patterns. The group mean was 37 units, ranging from 28-41. In common with previous tongue mapping data, the front center tip of the tongue was the most sensitive, with sensitivity dropping in the

posterior and lateral directions. Subjects were not able to discern any explicit difference in quality of the percept in this study between scan patterns.

The scan patterns differentiate from each other when subjects report their working level of stimulation. Moreover, the working levels appear to divide the scan patterns into two groups: lower and higher. The Progressive and Random scan patterns patterned together with a lower working level, 59 and 63 stimulation units respectively. The Interleave-A and Interleave-B patterned together with a greater working level, 73 and 71 respectively. Moreover, this pattern was evident in the individual data as well as the group means. This grouping pattern extended to the difference between working level minus minimum threshold level, or the dynamic range.

These results suggest that scan pattern can alter perception of stimulation intensity. The progressive and random stimulation patterns may induce spatial summation over time. As a result, the maximum working level is overall lower than when a small temporal offset is provided, as in Interleave-A and Interleave-B.

There are a few implications for these results. First, it provides evidence that micro-second electrode stimulation timing can alter perception, and therefore, neuro-stimulation procedures can be optimized for a particular task or constraint. Second, micro-second timing patterns may not be explicitly obvious to the perceiver. Thus, these results can influence the design parameters for a particular application. For example, if there is a design constraint to keep overall voltage as low as possible, one would choose the Progressive/Random stimulation pattern. However, if dynamic range were important to the application, one may implement an Interleave scanning pattern.

Temporal Perception Enhancement via Pulsing Scheme?

In reviewing the literature on temporal perception in other sensory systems, experimental methodologies were slightly different than our previously reported method. Therefore, in order to explore whether our results were specific to our methodology, we executed a comparative study.

In the previous 2AFC Flicker Fusion experiment (1mm center-to-center electrodes), the mean of 16 subjects exceeded threshold gap detection (defined as >75% correct) at temporal gaps of 75ms or better. The ―continuous" condition presented a repeating scheme of two 25µs stimulating pulses separated by a 100µs rest period repeating at 1736Hz. For the temporal ―gap" conditions, a repeating pulse scheme of stimulating for 500ms followed by no stimulation for 33-250ms, depending upon condition.

In that study, the temporal duty cycle for the gaps was not 50% as is often used in temporal discrimination experiments in the literature for other sensory systems. To better compare our results with the literature, we repeated that experiment with five new subjects for comparison, focusing on just the fastest temporal conditions: 33, 50 and 75ms using a 50% on/off duty-cycle scheme using the same linear electrode array.

As before, temporal gap discrimination performances were translated into a percent correct score for each temporal gap and subject. Effective discrimination was defined as a group performance threshold greater than 75% correct.

Unlike before, this small group (n=5) did not exceed performance on the 75ms gap, and data was not collected for longer gap durations (Figure 12).

Flicker Fusion Timing
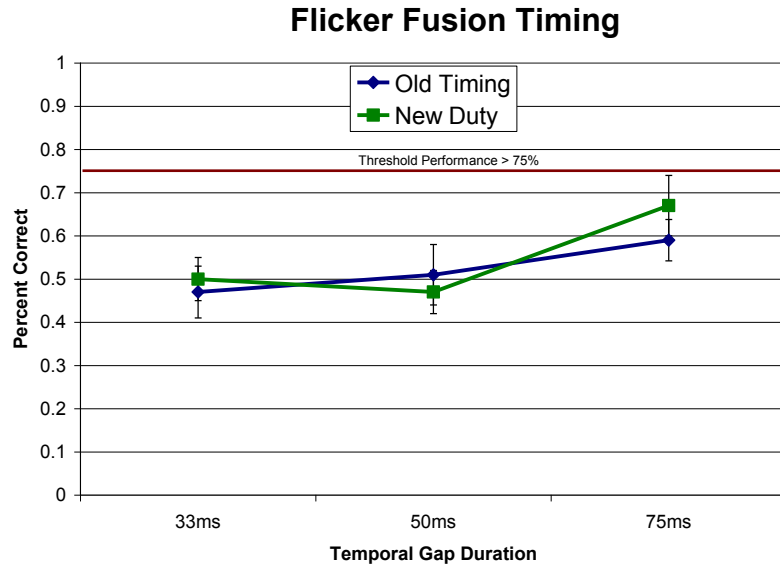
Figure 12. Flicker Fusion

Percent correct performance trends toward better performance using the 50% duty cycle scheme, but with the small sample size, this difference is not yet significant. However, an ANOVA (timing method versus duration) revealed a similar significant main effect for stimulus spacing ($F(2,8)=4.473$, $p<.05$). As the temporal gap increased, performance improved, regardless of timing method. This suggests that the duty cycle timing, at least for the new subjects surveyed, did not significantly increase performance.

While this new group of subjects did not perform above threshold, they follow the same psychophysical trend as before: as gap duration increases, performance improves. Testing with the 16 original subjects or adding additional subjects to this new analysis may eliminate this difference. For this experiment we were most concerned with comparing different temporal patterns than specifically replicating the older study. These results suggest that temporal perception may be a generalized skill that is minimally affected by small temporal changes.

In the finger-tip tactile sensory literature, temporal discrimination rates are faster than observed in our studies. Based upon limited observation with our multi-sized electrodes, we noticed that the size of the electrode appeared to be related to better temporal gap detection. Recall in our original experiment, we tried to run the flicker fusion experiment on the 254 micron array, but our pilot data suggested it was too hard. We then switched to the 1000 micron array and observed expected performance patterns. To more reliably quantify this relationship, in the next reporting period, we plan to compare flicker fusion performance across array sizes.

2.6   Enhanced Percept – Rifleman Training

Summary

8 subjects were trained to hold a rifle with 0 degrees of cant. 4 subjects, in the control group, were given verbal training and 4 subjects, in the experimental group, were given automated training with feedback from an integrated BrainPort-based tongue display. Both groups achieved skills at holding the rifle in a stationary vertical orientation and performance improved with training, thus proving the hypothesis. There is no clear difference between subjects trained by human interaction or those trained exclusively with electro-tactual stimulation.

Method

Preparation

An M-16 rifle simulator (G&G Armament GR16) was instrumented to detect rifle cant (tilt/rotation) using a modified BrainPort V100 vision system (Wicab). A special target was constructed with a high contrast horizon located 12.5 cm below the bull's-eye, out of sight of the shooter. The 2 cm bull's-eye was placed 32 cm from the floor. The target was mounted approximately 3 meters from the rifle tip.

The V100 camera was mounted to the front sight of the rifle, out of sight of the shooter, and software was configured to detect the tilt of the horizon in the video picture. This arrangement provided tilt accuracy and resolution of approximately 0.5 degrees.

Software was further configured to time the shots, and to collect and store shooter data.

In preparation for each subject, the rifle was configured to assign unique codes to the data files of the format:

nnnndtt—yyyymmdd-hhmmss.bpv

nnnn	= subject ID
d	= trial day (4 = final test data on day 3)
tt	= shot number
yyyymmdd	= year month date
hhmmss	= hour minute second

for example: 1001101--20090908-142831.bpv

subject 1001, day 1, shot 1 on 8/9/2009 at 2:28:31 pm

Additionally, the door and window blinds in the room were closed an all lights were turned on to provide a quiet, consistently lit environment.

Subject Orientation

Upon arrival, each subject was briefed in the overall requirements for the study and provided with an informed consent document.

After review and endorsement of the informed consent agreement, the subject was provided with a copy of *Army Rifle Marksmanship M16A1, M16A2/3, M16A4, and M4 Carbine training manual* and instructed to read sections 4-5-a and 4-5-b.

After approximately 10 minutes, the trainer reviewed the training manual information and clarified any difficult to understand concepts. Special attention was given to rifle cant and the relationship between bullet drop and sight alignment.

The subject was next given the rifle and instructed in the proper manner of holding it. Following that, the subject was instructed to assume a comfortable position on the floor, aiming at the target with the right hand supported by a sandbag. Note: all subjects were right handed and were placed in the same basic position. After insuring the natural point of aim was towards the target and that the subject was comfortable, instructions were presented on execution of the training. Finally, the subject was allowed to draw a slip of paper from a pile. The writing on the slip determined if they were in the control or the experimental group.

If the subject was in the experimental group, a final 5 minutes of instruction were given on interpretation of the stimulus presented to the tongue. As proof of understanding, the trainer watched on a remote PC as the subject was instructed to rotate CW, rotate CCW, and center the stimulus and verified appropriate outputs.

Baseline

At the beginning of each of the 3 daily sessions, the subject was asked to perform 10 shots with no guidance and/or stimulation.

Training

Following baseline, one of two training methods was employed with the subject.

Control training method

Prior to each sequence of 10 shots, the subject was given verbal information on the prior 10 shots. For example:

- You were rotated counter clockwise (CCW) about two degrees on the last 3 shots
- You varied +/- 1 degrees around zero degrees
- You started 2 degrees CCW and ended 1 degree CW
- AOK, keep doing what you are doing

Following the verbal instruction, the subject was asked to aim at the target while the instructor watched the PC. Then the instructor directed the subject until the rifle was held at the proper perfectly vertical orientation. The subject was told to relax and the instructed aiming was performed one more time.

Following the training, the subject was instructed to take 10 shots. Between shots the rifle software instructed the subject to lift his head away from the sight for approximately 5 seconds. A total of 12 training / shot sequences were performed across 3 days.

Experimental training method

Prior to each sequence of 10 shots, the subject was given verbal information on the prior 10 shots. For example:

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- AOK, it looks like the hardware is functioning properly

- Do you feel you understand how the stimulation guides you to correct your aim?

Following the verbal instruction, the subject was asked to aim at the target while the instructor watched the PC. Then the instructor directed the subject to rotate CW and then rotate CCW. The purpose was to insure the rifle software was functioning correctly. The stimulation was off during this task.

Following the verbal review, the subject was instructed to take 10 shots. The stimulation level was kept at a constant level (recorded in the log) that was determined by the subject with the instructor's guidance.

Between shots the rifle software instructed the subject to lift his head away from the sight for approximately 5 seconds. A total of 12 training / shot sequences were performed across 3 days.

Final evaluation testing method

All subjects performed 3 groups of 10 shots following the third day of training. The same baseline instructions were used, i.e. no feedback or other information was given by the instructor other than _you may proceed'. Between each group of 10 shots, the subject was instructed to stand for about 1 minute as the data was being transferred from the rifle to the PC.

All in all 18 series of 10 shots were fired by each subject.

Day 1 – Baseline 1, Training 1, Training 2, Training 3, Training 4

Day 2 – Baseline 2, Training 5, Training 6, Training 7, Training 8

Day 3 – Baseline 3, Training 9, Training 10, Training 11, Training 12, Final 1, Final 2, Final 3

Deviations

The protocol was executed faithfully with a few notable exceptions.

- Only 8 subjects (4/4) were tested as opposed to 10 subjects (5/5)

- Failures in the test apparatus resulted in the loss of certain data

    o Subject 2, samples 31-50

    o Subject 3, samples 111-120

    o Subject 8 used a cushion on day 3 for health/comfort reasons.

Analysis

An ANOVA statistical analysis was performed to compare the effects of training group (BrainPort stimulation versus verbal coaching) on performance across days (days 1-4), looking at average tilt across five seconds (Figure 13). There is a significant main effect for training duration ($F_{(3,18)}=5.012$, $p<.005$), where subjects made significant improvements, reducing the tilt of the rifle over time There is no main effect contrasting training group or a significant interaction suggesting that both training paradigms resulted in similar endpoints. In other words, all subjects benefited from either training protocol reducing the overall magnitude of tilt within four days training.

While not statistically significant, the differences between the two group's performances appear to diverge. This may be an artifact of noise or could reveal differences that may be apparent with more subjects.

Sharp Shooter Training
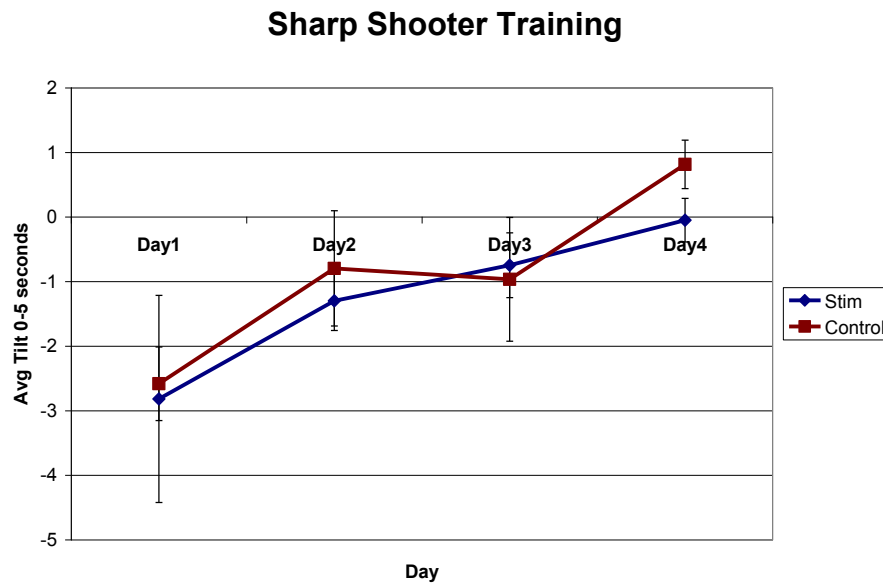
Figure 13. Training Group Performance

Discussion

These results suggest that providing electrotactile information to the tongue is an effective alternative method for providing rifle position training to a novice. Based upon this small study, there are no differences between subjects trained by human interaction or those trained exclusively with electro-tactile stimulation. As a result, training techniques could be modified to incorporate aspects of automated training, thus directing human interaction coaching to other aspects of rifle skill acquisition.

3   HARDWARE AND SOFTWARE DEVELOPMENTS

Hardware development over the course of this project went from simple linear arrays for initial spatial discrimination testing to three different High Density Electrode Arrays (20x100, 40x50, and 40x40) and an associated simultaneous control system. Later stages of the project integrated a BrainPort vision device (BPV-V100), allowing real-time image flow from a camera or other source to be presented on the tongue via a 400 electrode array.

3.1   High Density Array Control System

Significant engineering effort for this program focused on building the High Density (HD) Array Control System, used for discrimination testing.

The overall System Architecture is shown below, Figure 14. This system provides micro-electrode transcutaneous neuro-stimulation on a new scale: thousands of simultaneous active electrodes and up to 96 unique waveforms (limited only by device memory).

The Experiment Workstation runs the experiment control software application and provides a Common Software Interface, an Ethernet Connection to Control Modules, a Socket communications protocol. It is designed to scale with the control hardware.

The HD Controller Boards (Figure 15) are designed to manage 100 electrodes each. They include a Linux-based Microcontroller (Gumstix) executing custom control software (the Experiment Virtual Machine), an FGPA (10MHz waveform clock) providing Master-Slave synchronization across all control boards, simultaneous electrode activation, and the electrode drivers. The control boards are designed to allow each electrode to be an active electrode (stimulating), a return electrode, or floating (out of the circuit).
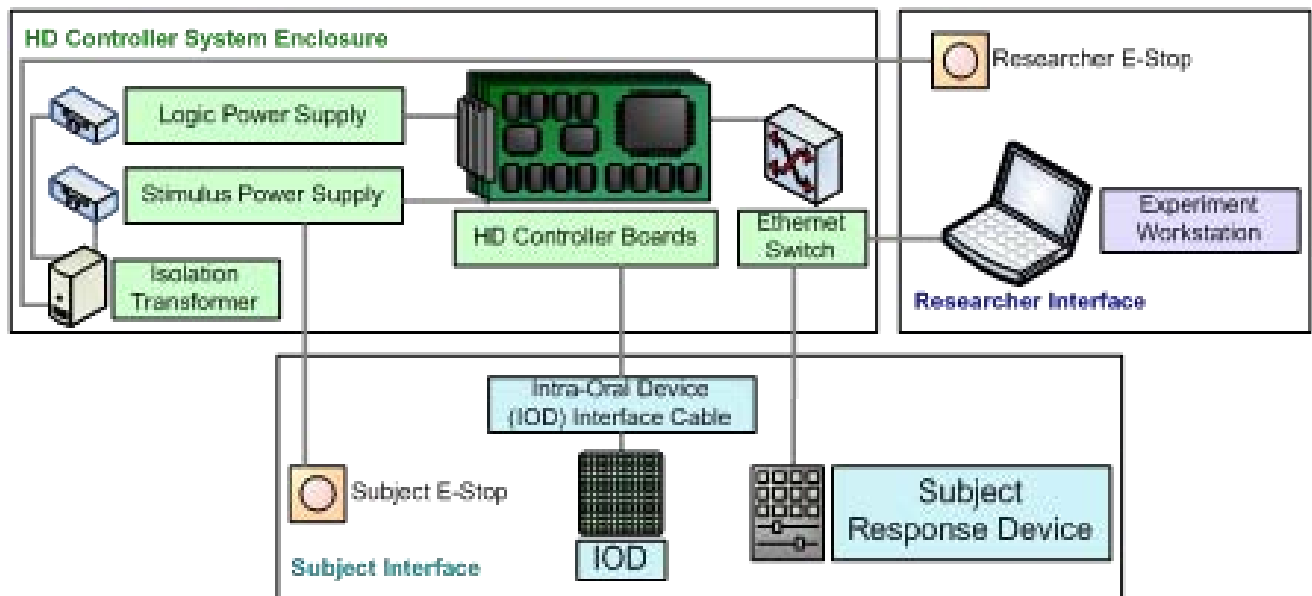
Figure 14. High Density Array Control System Architecture
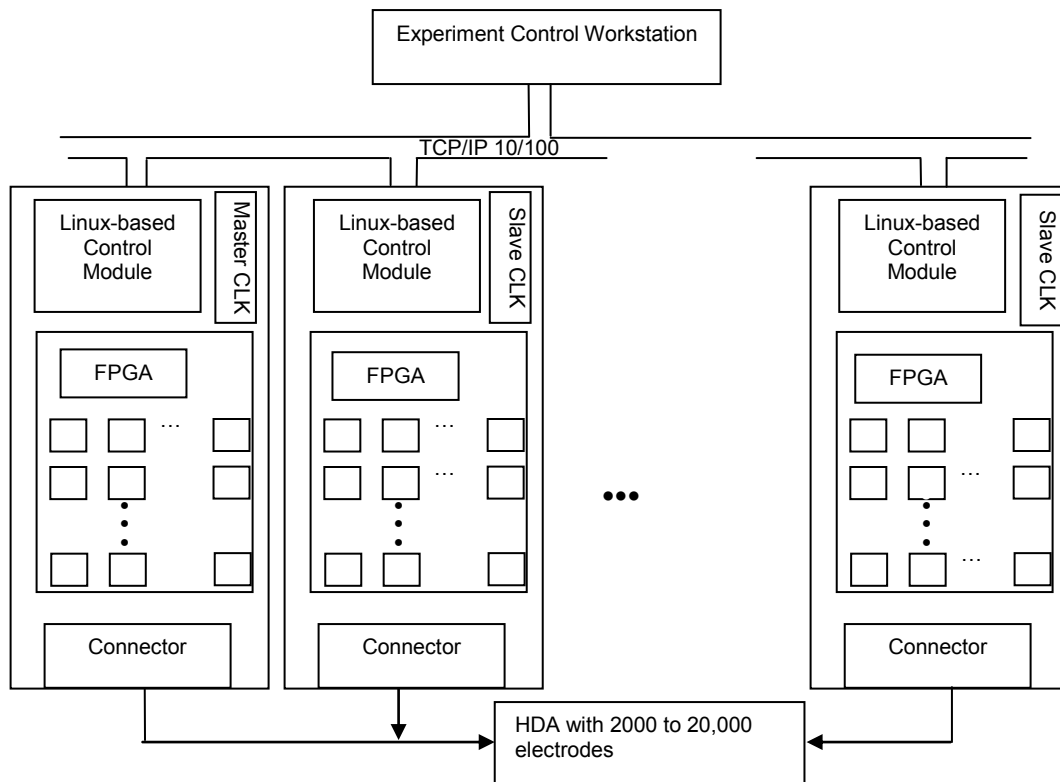
Figure 15. Core Hardware Architecture

3.2 Hardware

Significant Accomplishments: Design and manufacture of the HD Control boards. Each board manages the state of 100 electrodes and allows simultaneous activation of any or all at a given time. Figure 16 shows a completed HD Control board. We currently have 22 boards in house.
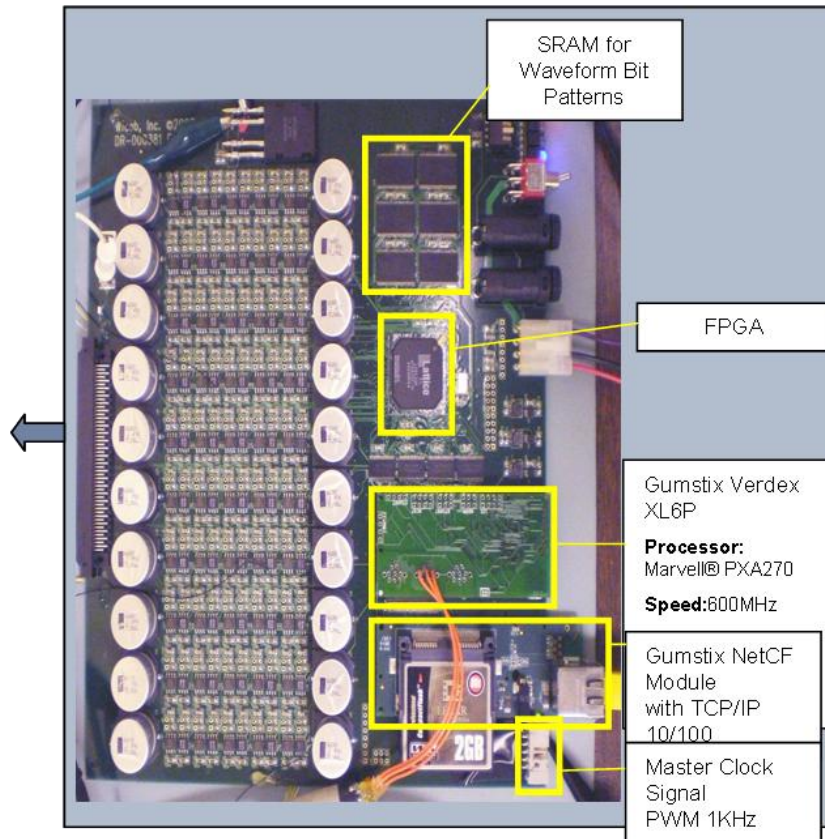
Figure 16. Complete HD Control Board

- To control the array stack-up described below, an HD Control board is required for every 100 electrodes. Figure 17 shows a board being inserted into the instrumentation rack. The initial system will handle 2000 electrodes (20 control boards). Each board has a cable connecting it to a set of electrodes (cables are seen hanging off the front of several boards).

Figure 17. Control Board Insertion

- When fully populated, the instrumentation rack, Figure 18, contains the electro-mechanical interfaces allowing the Experiment Workstation (a PC with custom software) to control each HD board and every electrode.

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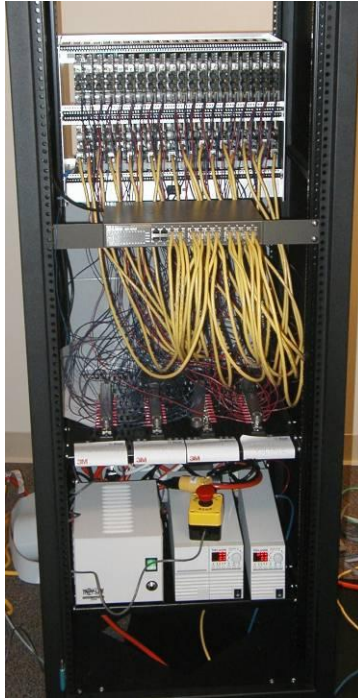
Figure 18. Populated Instrumentation Rack

This initial implementation was sufficient to support the planned experiments. During the course of the project, Wicab and DARPA agreed to limit testing to devices with 2000 electrodes before deciding whether fabrication of larger capacity arrays is necessary (Note that the system is designed to scale up to 20,000+ electrodes).

Wicab used this high density array system to conduct studies at the limits of spatial, temporal and contrast discrimination. In addition, the control architecture supports waveform shaping and simultaneous activation of many electrodes (compared to previous systems where only one electrode at a time is activated).

High Density Array Stack-up
Figure 19 shows a 100 element strip array in comparison to the early 100 element arrays. Up to 20 strip arrays were stacked and laminated to produce an array assembly used for testing. Figure (20.a) shows the completed proof of concept prototype validating the design and fabrication approach to the assembly.
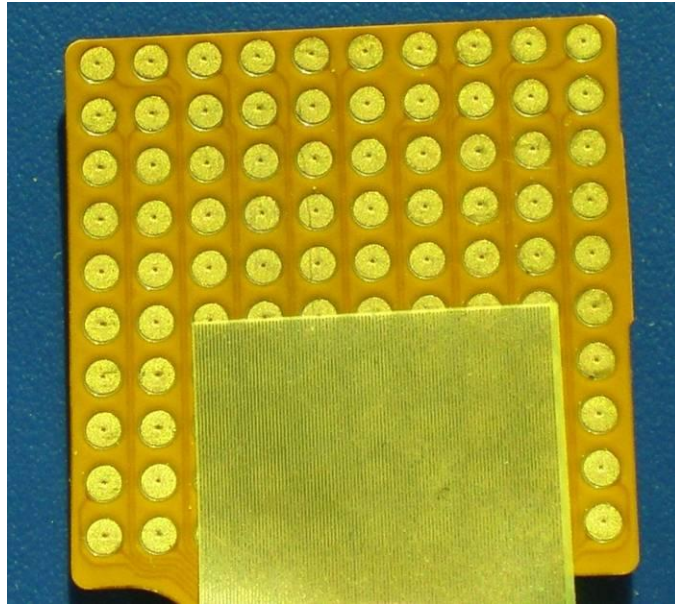
Figure 19. High Density Array – 100 element strip, compared to original 10x10 array
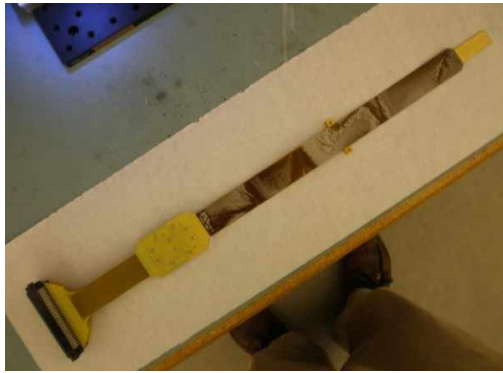
(a)

(b)
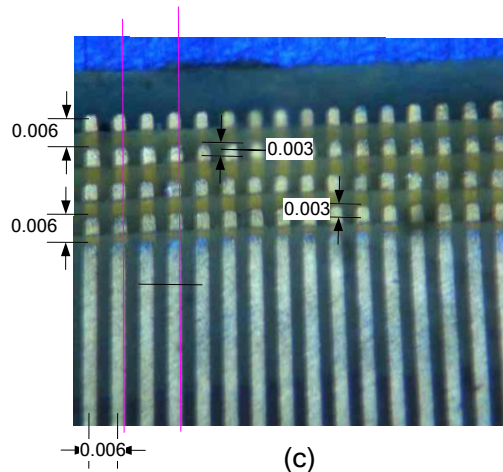
(c)

Figure 20. Strip Array Stack-up

At arms length the individual electrodes are barely visible (20.b) to the naked eye.

Figure 21 shows a single strip array, with a 20 layer stack of strips.
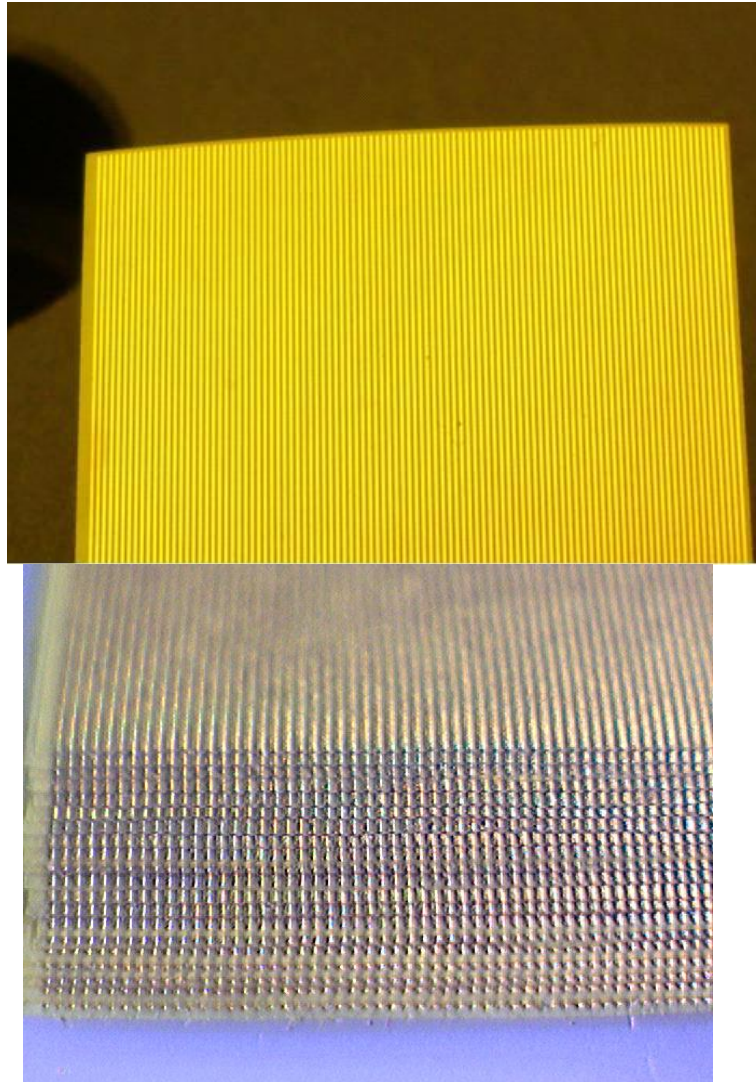
Figure 21. Stackup and single strip array

3.3   Software

Software modules have been developed for the experiment system throughout the TUNS project to support psychophysical experiments and provide the necessary mechanisms to run subjects on two tongue stimulation platforms (WG-C200 and HD Controller). Data formats were also developed to encode experiment parameters, waveform parameters/timings, stimulus patterns, etc. for use with the custom software being developed. The data formats and software modules designed during this project are summarized in this document.

3.4   Stimulation Platform

3.4.1   Virtual Machine Concept

In order to describe stimulation parameters in a generic enough format to produce similar system behavior across hardware implementations, a virtual machine design has been used. Tongue

stimulation patterns/timings are parameterized using a custom instruction set that executes in the virtual machine via a scheduled run-to-completion scheme. Programs written using the instruction set are described as ‗Stimulus Programs'. A fixed master clock drives the virtual machine, synchronizing voltage outputs at the electrodes. Only a few of the instructions are hardware dependent (those related to actually commanding the hardware voltage outputs and waveform selections) implying that the virtual machine can easily be ported to various hardware platforms. Figure 22 shows the stimulaus program workflow.

Figure 22. Stimulus Program WorkFlow

3.4.1.1   Instruction Set

The instruction set is outlined in detail in Appendix A – Virtual Machine Instruction Set. Instructions have been designed for such tasks as electrode addressing, voltage adjustment, waveform selection, clock adjustment and simple execution control (looping, conditionals, etc.). When used to create a Stimulus Program, execution of the instructions provides fully programmable voltage pulses at the electrode array/IOD limited only by the underlying hardware implementation.

3.4.1.2   VM State

The virtual machine state is outlined in detail in Appendix B – Virtual Machine State Definition. In order for the virtual machine to execute the instructions in a Stimulus Program, an associated virtual machine state is maintained. The state variables are referred to as ‗registers' since they serve the same purpose as processor registers for the virtual machine. These registers are broken down into several subsets; timing registers, loop control registers, address registers, voltage registers, count registers, block voltage registers, loop control registers, waveform registers and hardware specific configuration registers. Stimulus Programs can use these registers to affect how the voltage at an electrode is changed over time.

3.4.1.3   Stimulus Programs

A Stimulus Program defines a list of instructions designed to produce a specific stimulus timing pattern at the electrode outputs. Stimulus Programs define exactly how the electrode outputs will be adjusted over time based on values stored in the VM State registers and the master clock rate. The

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stimulus timing and voltage output features are limited only by the underlying hardware capabilities such as maximum clock speed and stimulation power supply.

3.4.1.4   Hardware Specific Features

For each platform for which the virtual machine is implemented, a small set of instructions must be implemented uniquely based on the underlying stimulation hardware. For example, a WG-C200 device uses a single DAC channel to adjust voltage output and a Multiplexer to select the single electrode that will receive the voltage output. In order for the Stimulus Program to adjust voltage on the platform, custom code must be implemented to communicate with the DAC and Multiplexer. The HD Controller voltage output cannot be adjusted directly, however it has the added feature of custom waveform.

3.4.2   HD Controller

In order to support high density arrays, a controller was designed to allow parallel boards to drive a set of simultaneously-firing electrodes, synchronized by a master clock. The implementation developed for this project utilizes a Gumstix ultra-mobile single-board-computer attached to a custom-fab board containing an FPGA, SRAM and associated drive electronics to drive 100 electrode outputs simultaneously at up to 10MHz.

The boards communicate with the workstation, acting as server, via 100Mbit Ethernet. Software on each Gumstix board executes a client application. To drive electrodes, each board has a 100 pin interconnect onto which a ribbon cable can be attached. On the other side of the ribbon cable, a number of different array configurations can be connected depending on the requirements of the experiment. For small linear arrays, a subset of the boards may be used to drive a small number of electrodes (e.g. 100 electrodes can be driven with a single board). For higher density arrays, any number of boards up to a total of 20 on the currently built system can be utilized to drive up to 2000 electrodes.

All boards are linked by a master clock bus and one board is specified as the master to drive the master clock. The FPGA on the master board outputs a programmable PWM signal to all other FPGAs on slave boards to synchronize electrode outputs across all boards. Each board has an SRAM directly attached to the FPGA to store waveform data. Waveform data consists of X/Y/Z states (X/Y/Z states correspond to high/low/ground) for the transistor on a given electrode over time producing a ―1-bit DAC‖ style output on the electrode when stimulation voltage is fixed. The internal clock on the FPGA provides transistor state switching at up to 10MHz when clocking waveform data from the on-board SRAM.

The virtual machine implementation on the Gumstix boards provides methods (via WGIO interface over Ethernet) to program the FPGA, load waveform data into the SRAM, set the master clock frequency, assign waveform selections per electrode and control the stimulation power relay (on/off). The software on the Gumstix also provides feedback to the workstation via a simple web-based interface (HTTP). The web interface provides feedback as to the status of the virtual machine and has been used for debugging and verification that the intended waveforms are being sent to the electrodes.

3.4.3   WG-C200

To support early experiment execution using available hardware, custom software/firmware was developed for the BrainPort Balance Device C200. A device executing the custom software/firmware is referred to as WG-C200. The WG-C200 device is capable of stimulating a single electrode at a time when used with discrete IODs (one wire per electrode) or up to 4 electrodes at a time when used with row/column based arrays. Voltage output level is adjustable by a DAC and the active electrode is selected using a multiplexer (4 DAC channels are used on row/column arrays).

The WG-C200 device communicates using the WGIO protocol (see Appendix C – WGIO Packet Definitions) with the workstation via an RS232 serial cable @ 115200 baud. Up to 100 electrodes can be driven when connected to the 120 pin connector on the device (for discrete arrays). Row/column arrays can be driven with a row/column adapter and an appropriately programmed device (supports both 18x18 and 25x25 row/column based arrays). For small linear arrays, a subset of the 100 electrode outputs may be used to drive a small number of electrodes (e.g. 10 electrode linear arrays). The DAC can be adjusted in timing increments down to 10µsec to produce a

- DAC and Waveform Timing
- Virtual Machine Implementation

3.5   Software Modules

The software modules developed for the experiment system can be broken into two subsections, pc-based (workstation) and embedded (HD Controller). The windows software applications provide an interface to the researcher and/or developer for executing experiments (Experiment Controller) and testing system operation (HD Diagnostic Utility).

3.6   Workstation PC Software Modules

3.6.1   Experiment Controller

The Experiment Controller application reads configuration from a Trial Configuration file (see the Data Formats section for more details). The researcher selects an experiment (with a corresponding Trial Configuration file) and steps through the software. Experiment specific parameters are entered by the researcher and the subject is presented with a set of trials for which they respond using an input device. The Experiment Controller software records the subject response for each trial and generates an experiment report upon completion. In order to present trials to the subject, the Experiment Controller communicates with the HD Controller sending it trial-specific parameters which determine the stimulus pattern and waveforms used, Figure 23. Experiment Controller also controls logic and stimulation power supplies for the HD Controller via RS232 serial link.

Experiment Controller HDServer/Client communication
steps during execution of a trial
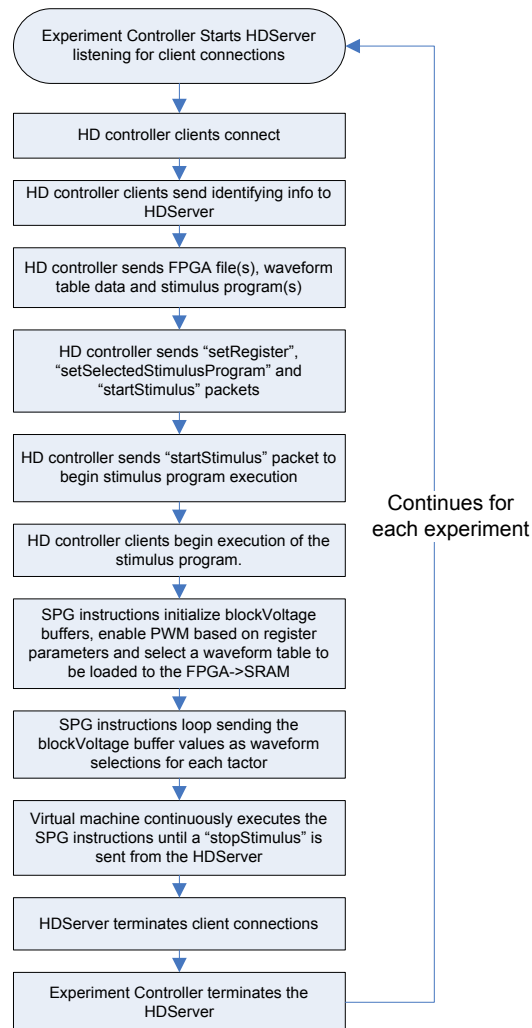
Figure 23. HD Server/Client Communication

3.6.2   Utilizing the VM to Present Trials

The ‗Virtual Machine‗ running on the HD Controller system (see the Virtual Machine section for more details) controls communications with the on-board FPGA/SRAM and sequencing of electrode selections to the attached IOD. This is accomplished through execution of a Stimulus Program in a scheduled run-to-completion scheme. Stimulus patterns and timings are defined as parameters to the Stimulus Program designed for a particular experiment. For each trial in an experiment, the Experiment Controller sends down appropriate stimulus parameters to cause the Stimulus Program to present the intended stimulus to the IOD.

3.6.2.1 Subject Input Devices

Two forms of subject input device are possible with the Experiment Controller; the hand-held controller and the numeric keypad. The Trial Configuration file for a given experiment defines which subject input device is to be used.

3.6.2.2 Power Supply Control

The HD system includes two programmable power supplies; the logic power supply (powers logic circuits on the HD Controller boards) and the stimulation power supply (powers the waveforms to the IOD).

3.6.2.3 Platform Specific Operations

The Experiment Controller contains several features specific to the WG-C200 platform such as serial port communications and use of ‗DAC' values as intensity control. It also includes features specific to the HD Controller system such as power supply control and ramping features, support for waveform data transfer and FPGA file support.

3.6.3 HD Diagnostic Utility

The HD Diagnostic Utility began as a utility to visualize Trial Profiles (see Trial Configuration section for more details) to ensure accuracy when developing electrode selection patterns on high density arrays (up to 2000 electrodes). This utility provides a method to select waveforms per electrode in a similar fashion to a paint program and allows importing of images to create a Trial Profile. Other features include communication with HD Controller boards and functions to test operations such as sending waveform data, FPGA data or Stimulus Program data to the board(s).

3.6.4 HD Controller Library and the WGIO Protocol

The HD Controller Library implements the windows side of the WGIO Communications Protocol. This protocol provides a set of packet definitions allowing Windows applications to command the HD Controller to start/stop stimulation, update the Waveform Definitions, upload an FPGA Program file, update Stimulus Programs and assign many other parameters affecting how stimulation is presented to the IOD. The WGIO protocol provides a handle into the state machine of the Virtual Machine executing on the HD Controller boards. For a detailed list of WGIO packets, see Appendix B – WGIO Protocol Packet Definitions. The HD Controller Library provides an event-based I/O model to the parent application and implements a socket-based communications layer to the HD Controller boards via Ethernet acting as a server in a client-server model.

3.7   HD Controller Board Modules

3.7.1   Gumstix Platform

Each HD Controller board requires a microprocessor to configure the FPGA to sequence the electrode outputs and communicate with the PC Workstation. For this task, a ‗Gumstix‘ brand single-board computer has been chosen for its speed, size and versatility in communications methods (Ethernet, serial, address/data bus, etc.). The board includes a 32-bit Marvell PXA270 processor running at 600 MHz with 128MB SDRAM and 64MB flash. The board runs embedded Linux providing TCP/IP communication and Compact Flash support for ease of development and integration. The FPGA is connected to the PXA270 via its Address/Data bus as well as a JTAG interface from which the Gumstix board programs the FPGA during the boot process.

3.7.1.1   HD Client Application

The primary software application running on the Gumstix platform is the HD Client application. This software implements the virtual machine, programs and configures the FPGA based on remote TCP/IP communications via the WGIO protocol and provides an HTML based status web page. This software maintains communications (as client) with the Experiment Controller (as server) on the PC. As an experiment is run, the Experiment Controller sends commands via the WGIO protocol to the HD Client application and the state of the FPGA is updated to reflect the commanded changes. These changes to the state of the FPGA are moderated by the virtual machine as it ticks through scheduled run-to-completion steps of a selected Stimulus Program.

3.7.1.2   Client Diagnostic Application

The Client Diagnostic application was developed in the early stages of testing the FPGA to provide an easy interface to changing memory locations before the full ‗HD Client‘ application was developed. Features include control over PWM output of the FPGA, waveform selection per electrode, loading waveform data from a file to the SRAM attached to the FPGA and LED output control. This utility is mainly useful for debugging/troubleshoot HD Controller boards exhibiting unexpected behavior.

3.7.1.3   Virtual Machine Implementation

The implementation of the virtual machine (VM) on the Gumstix platform provides implementations of all ―general purpose‖ and several hardware dependent instructions. Each HD Controller board provides a trigger input which triggers execution of the virtual machine ―ticks‖. The primary instructions that support electrode output on the HD system are related to waveform selections for each electrode via the Block Voltage registers, Master Clock/PWM frequency control via the Tick Unit register and control of starting/stopping stimulus programs to sequence waveform selections.

3.7.1.4   Ethernet Communications

The set of HD Controller boards each has a standard Ethernet jack on it attached to the Gumstix board controlling it. These Ethernet jacks are connected to a 24 port switch to form a local network along with the workstation PC and the hand-held controller. The Experiment Controller (as server) communicates with each board individually (as client) via TCP/IP. The Experiment Controller (as client) communicates with the hand-held controller via TCP/IP.

3.7.1.5 DHCP server

The PC Workstation runs a simple DHCP server that supports fixing IP address to MAC address for each HD controller board. The subnet used for the local communications is 172.16.5.0/255.255.255.0. The hand-held controller address is fixed at 172.16.5.1 and the PC workstation is fixed at 172.16.5.5. The HD Controller boards are assigned IP addresses sequentially board 0 through 19 respectively numbered 172.16.5.10 through 172.16.5.29.

3.7.1.6 PC to HD Client Connections

Upon booting up and running the ―HD Client" application, each HD Controller board attempts a TCP/IP connection (as client) to the Experiment Controller (as server) on the PC workstation on TCP. Upon connecting, the client communicates via the WGIO protocol and waits for commands from the Experiment controller.

3.7.1.7 HHC to PC Connection

Upon booting, the hand-held controller listens (as server) for connections from the Experiment Controller (as client). Once connected, the hand-held controller sends ASCII formatted text packets reporting the status of the slider, knobs and buttons as states change. The Experiment Controller can use this data to record a subject's response to a stimulus.

3.7.1.8 Linux Kernel Module and Interrupts

To maintain synchronized operations across boards, an interrupt is triggered with each tick of the Master Clock/PWM line.

3.7.1.9 WGTrigger Kernel Module

The Master Clock/PWM line is used to synchronize operations across HD Controller boards. This line triggers both the FPGA to start a waveform pulse and the PXA270 on the Gumstix board via a GPIO pin to tick the VM. A Linux kernel module (wgtrigger.ko) has been developed to monitor GPIO 22 to which the Master Clock line is connected and trigger an interrupt on the rising edge. This interrupt triggers the kernel module to update waveform selections in the FPGA via writes to the Address/Data bus and signal the virtual machine to execute its next "tick" in its currently selected Stimulus Program.

3.7.1.10 /proc Filesystem

The wgtrigger.ko kernel module utilizes a custom file /proc/wgtrigger to provide a pipe for communication between user and kernel space. The kernel module uses it to signal the HD Client application to execute the next VM tick. The HD Client application uses it to update the set of waveform selections for each electrode to be presented on the next Master Clock/PWM tick.

3.7.2 Hardware Interconnects

3.7.2.1 Address/Data Bus

The FPGA and PXA270 are connected via a 26 bit address and 32 bit data bus. A 16 bit Address/6x16 bit data bus attaches the 6 Static RAM (SRAM) chips to the FPGA (See TR-070054 for more details). Address locations have been defined within the FPGA for various features corresponding to logic blocks that have been programmed into it for electrode control, LED output, Master Clock/PWM generation and waveform data storage to the SRAM.

3.7.2.2 JTAG Interface

A JTAG interface (TDO/TDI/TCK/TMS) is used to program the FPGA. In order for the PXA270 to program the FPGA, 4 GPIO pins have been tied to the FPGA programming pins and a customized version of Lattice's ispvm_ui programming tool has been developed for the Gumstix platform.

3.7.2.3 Electrode Interface

Each HD Controller board has a 100 pin connector that interfaces to a 100 conductor ribbon cable. On the opposite side of the ribbon cables is an adapter providing connection to either a 10 electrode linear array (similar to that used in the WG-C200 device) or a high-density flex array.

3.7.3 Board-to-Board Waveform Synchronization

Each HD Controller board supports a total of 100 electrodes. In order to support greater than 100 electrodes in parallel, a set of boards uses a Master Clock/PWM signal to synchronize its electrode outputs.

3.7.4 Master Clock/PWM Signal Output

One HD Controller within the set is configured as ―Master" which drives its Master Clock/PWM signal as an output (all other boards are configured as ―Slave" which disconnects their Master Clock Signal driver). The signal frequency and duty cycle is programmable, typically 50% duty cycle running at <= 1kHz.

3.7.4.1 Responding to PWM Signal Input

The FPGA and PXA270 are both configured to respond to opposite edges of the Master Clock/PWM signal. The FPGA starts firing electrode output waveforms on a falling edge of this signal. The PXA270 triggers a ―tick" execution in its VM and loads up waveform selections to the FPGA in preparation for the next falling edge where the output will be presented.

3.7.5 Waveform SRAM

Waveforms are generated on electrode output by sequencing the ―high", ―low" and ―ground" transistors within the signal path. These 3 values are controlled as configuration bits that can be changed at a rate up to 10MHz by the FPGA. To toggle these lines over time, the FPGA sequences through a series of addresses on the attached SRAM modules and clocks out the data stored in the SRAM directly to the transistors for each electrode.

3.7.5.1 Writing to SRAM from the Gumstix

The SRAM consists of 6 individual chips with 16 bits of address/16 bits of data 64k deep. The FPGA provides an address window to the Gumstix for writing/reading to/from the SRAM. From the Gumstix perspective, the SRAM looks like a contiguous chunk of memory as seen below, Figure 24.

Support for 127 Waveforms in SRAM

	0x10XXXXX0	0x10XXXXX4	0x10XXXXX8	0x10XXXXXC
0x10000030	**X** (High) Bank3	**Y** (Low) Bank3	**Z** (Ground) Bank3	Ω (Not Connected) Bank3
0x10000020	**X** (High) Bank2	**Y** (Low) Bank2	**Z** (Ground) Bank2	Ω (Not Connected) Bank2
0x10000010	**X** (High) Bank1	**Y** (Low) Bank1	**Z** (Ground) Bank1	Ω (Not Connected) Bank1
0x10000000	**X** (High) Bank0	**Y** (Low) Bank0	**Z** (Ground) Bank0	Ω (Not Connected) Bank0
	├──32 bits──┤	├──32 bits──┤	├──32 bits──┤	├──32 bits──┤

Figure 24. SRAM Memory Map

3.7.5.2 Waveform Selection Multiplexer

A section of address space 100 bytes in size @ 0x10100000 has been defined on the FPGA to specify which of the 128 waveforms in the waveform table should be output on each electrode. The Gumstix writes 25 values (32 bits each) to change the waveform that is presented to each electrode.

3.7.5.3 Clocking of Waveforms to Transistors

SRAM data starting at address 0x10000000 is clocked out to all transistor inputs (X/Y/Z) in a series of 4 clock cycles on the FPGA's 40MHz clock. On a falling edge of the Master Clock/PWM signal, the FPGA starts its waveform output sequence sequentially clocking out data from SRAM to the transistors for 800μs. The data in the SRAM is configured by the Gumstix via the address/data bus before the Master clock/PWM signal is started. By default, the first waveform in any waveform table should be programmed to select the ―ground" value for all ticks within the waveform in order to ensure that the system can always disable stimulation by selecting waveform 0 for all electrodes.

3.7.5.3.1 Master Waveform Clock

The Master Waveform clock runs at 10Mhz derived from the 40MHz clock rate of the FPGA. It takes 4 clock cycles to clock the X, Y and Z states out to all 100 electrodes (100 x 3 bit channels). This is derived from 1 bit for X, 1 bit for Y, 1 bit for Z needing to be clocked out for 100 different electrodes (3 x 100 bit channels written out 128 bits at a time in 4 clock cycles).

3.7.5.3.2 Waveform Data Length Limitations

The depth of the SRAM is 64K which determines the maximum length of a waveform that can be presented to the electrodes. The configuration chosen provides storage for up to 128 unique waveforms up to 1.6ms in length. This is derived from 6 chips x 16 bits x 64K depth = 6291456 bits of data (786432 bytes) divided by 128 waveforms divided by 3 bits per tick giving 16384 ticks worth of transistor states stored. Since the waveform clock is effectively 10MHz, 16384 ticks will take 1.6384ms.

3.7.6 Power Supply Control

To power the HD Controller system, two separate power supplies are used. Each supply is plugged into a hospital grade isolation transformer to isolate the subject. Each power supply is connected to

the PC workstation via RS232 link. This RS232 connection allows the Experiment Controller and other utility software to control the current limits and voltage level for the supplies remotely.

3.7.6.1   Logic Power Supply

The logic power supply provides a constant 5.0V to the HD Controller boards to power the Gumstix boards, FPGA and related hardware via on-board regulators.

3.7.6.2   Stimulation Power Supply

The stimulation power supply correlates to the stimulation level that is output at the IOD. The supply can be adjusted during an experiment to find a level that is perceived as ―comfortable working level‖ to a subject.

3.7.7   DIP Switches/LED Indicators

3.7.7.1   FPGA Programmed Indicator

The blue LED turns on after the FPGA has been successfully programmed.

3.7.7.2   Stimulation Active Indicator

The amber LED turns on anytime the stimulation relay is open and providing stimulation.

3.7.7.3   Stimulation Supply Charged Indicator

The yellow LED on the front of the HD Controller board indicates when the capacitors are charged and ready to stimulate. This LED fades as the capacitors drain.

3.7.7.4   Master/Slave Indicator

The red LED indicates whether an HD Controller board is configured as a master or slave. If a board is configured as master, the red LED will be on and its Master Clock/PWM output will be connected, otherwise the red LED will be off.

3.7.7.5   Master/Slave Switch

The first DIP switch is used to set whether the HD Controller board will be configured as master or slave. If the board is used on its own, it must be configured as master and a jumper must be installed in the jumper block to complete the Master Clock/PWM loop-back connection.

3.7.8   FPGA

3.7.8.1   PWM Signal Programming

The Master Clock/PWM signal is programmable from the Gumstix at address 0x10300000. The PWM signal is generated using two counters which determine the ―high time‖ and the ―low time‖ for the signal based on the 40MHz base clock. This provides the ability to program the PWM output with quite high resolution in the required frequency range for the system (typically <= 1kHz).

3.7.8.2   Waveform Selection Multiplexer

The FPGA has a set of multiplexers providing the ability to select any one of the 128 waveforms loaded into the SRAM for output to any electrode. This implies that each electrode can have a completely unique waveform or can be programmed to have the same waveform as other electrodes

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based on the multiplexer input values. To specify the waveform that is used for a given electrode, an 8 bit value must be written to the corresponding location in memory location 0x10100000.

3.7.8.3   LED Indicator Controller

The FPGA provides access to changing the state of the output LEDs as bits in a bitfield at location 0x10200000.

3.8   JTAG Programming

- Lattice semiconductor provides source code for a JTAG programming module (ispvm_ui) that could be customized to work with the HD Controller platform. Four GPIO pins available on the Gumstix board were programmed as I/O and the ispvm_ui tool's source code was configured to utilize these pins for TDI, TDO, TCK and TMS.

- The HD Client application implements a command that can be triggered from the Experiment Controller to transfer an FPGA program in the form of a .VME file. Once the .VME file is transferred to the HD Client application, the ispvm_ui command line utility is called to perform the programming step placing the .VME code into the FPGA via the JTAG interface.

Deprecated Software Modules

As of the development of the HD Controller system, the WGC200 platform is no longer used to collect data. The software modules developed for the WGC200 are frozen and will be considered ‗deprecated' as we do not plan to further develop the software. Software modules developed for the WGC200 platform include:

Software Module	Description
WG-C200 Firmware	Provides a subset of the Wave Generator I/O (WGIO) interface enabling experiments to be developed for a modified BrainPort Balance.
WG-C200 Simulator	Simple waveform simulator running on Windows that outputs electrode stimulation levels graphically. This application was no longer needed once the WG-C200 firmware was verified to be working properly.
Array Controller API Test	Simple Windows Forms application providing a graphical interface to the WGIO protocol sending/receiving packets to/from the WG-C200 device.
Trial Configurator	This tool was used to assist in creating the two point discrimination experiment for the WG-C200 but was never finished.

3.9 Data Formats

- o Trial Configuration
  - ▪ Stimulus Program
  - ▪ FPGA Program Files
  - ▪ Waveform Definitions
- o Experiment Controller Report
- o IOD Definition Files

3.10 Large Area Array and V100 Software Support

Several enhancements were made to the TUNS Experiment Controller and related software in support of the X16 experiment system (40x40 array) and features for waveform optimization. Additions include interfacing with a BrainPort Vision Device V100 (BPV-V100) to display real-time images from the head-mounted camera to the 40x40 intra-oral device (IOD) array, support for adjusting the scan pattern on 20x20 IODs (waveform optimization support) and vSight enhancements geared toward TUNS experiments (feature packs, tongue mapping, etc.)

3.11 X16 BPV-V100 Interface

New features have been developed for the TUNS Experiment Controller software allowing the experimenter to connect to a BPV-V100 device during a trial. When enabled, the subject wears a V100 with specially configured software that sends the camera images over WiFi for presentation to the TUNS HD Array Controller (tower). A software module converts the optical image from the V100 to a 40x40 tactile image that is presented to the user via the X16 array. The user interfaces with the standard V100 controls for stimulation intensity control on the 40x40 array attached to the TUNS HD array controller (tower). This enhancement enables experiments based on visual tasks to be performed

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using the 40x40 electrode tongue array and allows a comparison to be made between the X16 (40x40) array and the V100 intra-oral device (IOD) which only has 20x20 electrodes.

3.12 TUNS vSight Feature Packs

A new version of the vSight vision display software has been released as part of the BPV-V100 product that provides an interface to developers for adding custom GUI panels at run-time in support of experiments. Utilizing this feature set, custom panels have been designed for TUNS experiments to tailor the interface for tongue mapping and waveform optimization tests.

A Waveform Optimization GUI panel has been developed that allows control of a special load of software on the BPV-V100 device to vary stimulation pulse parameters at runtime. This panel allows the researcher to provide A/B comparison stimuli to a subject and collect data from the subject as needed.

A Tongue Mapping GUI panel has been developed that provides an interface to stimulation of fixed regions of the tongue for a min/working style experiment. The researcher selects a region of the tongue and asks the subject to set a ―minimum‖ or ―working‖ intensity level (depending on the experiment parameters) and then records the intensity level displayed on the screen to ―map‖ the tongue‗s sensitivity to the stimulus.

4   WAVEFORM OPTIMIZATION

Special software has been written for the BPV-V100 device to provide various electrode scan patterns to enable testing of whether waveform scan patterns affect perception on the tongue array. These scan patterns include standard progressive scanning (adjacent electrodes are pulsed immediately after one another), interleaved scanning (adjacent electrodes are not pulsed immediately after one another), and random scanning (pseudorandom electrode scanning pattern).

A simple waveform editor has also been developed that allows creation of .XML files compatible with TUNS Experiment Controller to drive the HD Array Controller (TUNS tower).

5 PUBLICATIONS

Arnoldussen, A., Hogle, R., Fisher, F., Lederer, S., Rosing, M., Besta, M., Ferber, A. (2008) *Spatial Resolution on the Tongue as Applied to a Prosthetic BrainPort® Vision Device*. ARVO Abstr. 2898/A101.

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Van Boven RW, Johnson KO.; "The limit of tactile spatial resolution in humans: grating orientation discrimination at the lip, tongue, and finger," Neurology, 44(12):2361-6. Dec 1994.

Ezawa, M.; "Rhythm perception equipment for skin vibratory stimulation," Engineering in Medicine and Biology Magazine, IEEE , vol.7, no.3, pp.30-34, Sep 1988 doi: 10.1109/51.7932

Appendix A – Virtual Machine Instruction Set

Instruction	Arguments	Description
AC		Set address to a constant value
AR		Set address to a register value
VC		Set voltage to a constant value
VR		Set voltage to a register value
RV		Set a voltage register vavlue
RA		Set an address register vavlue
TU		Set the time unit register
TR		Set the tick resolution register
LD		Delay a constant number of ticks
LS		Start loop with a constant count
LE		End loop, decrement count, jump to start if count > 0
ET		End Tick
RC		Set a count register value
LDR		Delay with tick count loaded from count register
LSR		Start loop with count loaded from count register
TRR		Set the tick resolution from a count register
OIC		Increment a COUNT[] register value
ODC		Decrement a COUNT[] register value
ARC		Set address from ADDRESS[COUNT[x]]
VRC		Set voltage from VOLTAGE[COUNT[x]]
RSVD1		No-op (reserved)
RSVD2		No-op (reserved)
RSVD3		No-op (reserved)
RSVD4		No-op (reserved)
BNE		Branch if COUNT[x] != 0
BEQ		Branch if COUNT[x] == 0
ELSE		Else condition for if
ENDIF		Terminator for if
RCC		Copy value from COUNT[b] into COUNT[a]
RJMP		Relative jump past n instructions
ABI		Address increment (block mode)
ABR		Reset address (block mode)
VB		Assign channelVoltage[] values from BlockVoltage[blockIndex][0-channelCount][tactor]
BCC		Assign channelCount from a constant
BSC		Assign blockSize from a constant
BIC		Assign blockIndex from a constant
MODE		Assign array mode from a constant
BBC		Assign blockBufferCount from a constant
ABAC		Assign absolute address in block mode from a constant
BSR		Assign blockSize from a count register
BCR		Assign blockCount from a register
BBR		Assign blockBufferCount from a count register
BIR		Assign blockBufferIndex from a count register
BCP		Assign BlockVoltage[ARG0][][] values to VOLTAGE[BlockVoltageRef[ARG1][][]
BCPR		Assign BlockVoltage[COUNT[ARG0]][][] values to VOLTAGE[BlockVoltageRef[COUNT[ARG1]][][]
VBR		Assign channelVoltage[] values from VOLTAGE[BlockVoltageRef[blockIndex][0-channelCount][tactor]]

WVUP		Update waveform selections from BlockVoltage[bufidx][0][]
PWM		Start PWM with freq=COUNT[ARG0] duty=COUNT[ARG1]
WVTS		Activate a waveform table from the VM table list (send it to the FPGA)
BNEO		Branch ARG2 steps if COUNT[ARG0+COUNT[X]] != 0
ODCO		Decrement a COUNT[ARG0+COUNT[ARG1]] register value
BVR		Set a BlockVoltageRef[ARG0][ARG1][COUNT[ARG2]] register to ARG3
RCO		Set COUNT[ARG0+COUNT[ARG1]] register to ARG2
RCCO		Set COUNT[ARG0+COUNT[ARG1]] = COUNT[ARG2+COUNT[ARG3]]
BEQO		Branch ARG2 steps if COUNT[ARG0+COUNT[X]] == 0
BVRR		Set blockVoltageRef[ARG0][ARG1][COUNT[ARG2]] to COUNT[ARG3] + COUNT[ARG4]

Appendix B – Virtual Machine State Definition

Data Type	Name	Description
UINT32	pc	Program counter (in bytes)
UINT32	lc	Loop counter (current index into loopcount, increments when a new loop is started, decrements when a loop completes)
UINT32	tu	Time unit (defaults to microseconds)
UINT32	tr	Tick resolution (# of ticks in „tu' units between VM ticks)
UINT32	et	End tick (ends a run-to-completion series)
UINT32	dr	Delay register (holds # of ticks to delay)
UINT32[]	loopStart	Stores pc when a loop starts
UINT32[]	loopCount	Loop counts (dimension determines max # of nested loops)
UINT32[]	regV	Voltage registers
UINT32[]	regA	Address registers
UINT32[]	regC	Count registers
UINT32	ainc	0 – do not increment address, 1 – increment address (used for row/column IOD block mode)
UINT32	arst	Address reset (0 do nothing, 1 reset tactor address to 0 on next tick)
UINT32	dacval	Current DAC value
UINT32	tactor	Current tactor address
UINT32	arrayMode	Current array configuration mode 0: Discrete tactor scanning mode 1: Block tactor scanning mode 2: Discrete parallel mode 3: Block parallel mode
UINT32	addressMode	Current tactor addressing mode
UINT32	voltageMode	Current tactor voltage mode 0: Single DAC 1: Multiple DAC 2: Simultaneous
UINT32	blockSize	Number of tactors in a block for block addressing mode
UINT32	blockBufferCount	Number of block voltage buffers to allocate (corresponds to number of full "frames" of waveform selections for each tactor)
UINT32	blockBufferIndex	Index into the blockVoltage array indicating the currently selected block voltage buffer to present
UINT32	channelCount	Number of channels/blocks for multi-DAC mode
UINT32[]	channelVoltage	Current DAC value for each channel in multi-DAC mode
UINT32[][][]	blockVoltage	Array of values sized by [blockBufferCount][channelCount][blockSize] used to indicate which voltages should be applied to each tactor and/or which waveforms should be applied to each tactor
UINT32[]	blockVoltageRef	Array of indices into regV[] that can be used to copy regV[] values into a blockVoltage[][][] buffer
UINT32	fpgaFileCount	Number of FPGA files (.VME) loaded
CHAR[][]	fpgaFilename	Filenames of .VME files loaded
UINT32	waveformTableCount	
UINT32	waveformTableCount	Number of waveform tables that are loaded
UINT8[][]	waveformDataTable	Points to dynamically allocated waveform table arrays
UINT32[]	waveformCounts	Number of waveforms in each table
UINT32	waveformSizes	Sizes of each waveform in bytes

Appendix C – WGIO Packet Definitions

Command	Arguments	Description
RDP		Return Data Packet
SPLS		List loaded Stimulus Programs
SPSET		Set the current Stimulus Program
SPLD		Load a Stimulus Program
SPDEL		Delete a Stimulus Program
RASET		Set one or more address registers
RVSET		Set one or more voltage registers
RCSET		Set one or more count registers
SPSTAT		Get device status packet
SPGO		Start/Resume the VM
SPHALT		Stop/Pause the VM
PINGCFG		Configure PING packets
PING		Ping packet
RESET		Reset the VM
CLEARSP		Delete all Stimulus Programs
RAGET		Get the value of an address register
RVGET		Get the value of a voltage register
RCGET		Get the value of a count register
RBSET		Set one or more block voltage buffer registers to a value
BREFSET		Set one or more BlockVoltageRef[][][] registers to a value
RBGET		Request a packet containing the value of a block voltage buffer value
CCONFIG		Client configuration packet
VMEFILE		FPGA .VME file packet
WAVETBL		Waveform data table packet
CLRDY		Client ready packet
RBREF		Set one or more values in BlockVoltageRef[] to a value from the VOLTAGE[] array

LIST OF ABBREVIATIONS

AFRL	Air Force Research Laboratory
API	Application Program Interface
DARPA	Defense Advanced Research Projects Agency
HD	High Density
HDA	High Density Array
IOD	Intra-Oral Device
IRB	Institutional Review Board
Electrode	Electrode on stimulation array, comparable to pixel on visual display
TUNS	Tactical Underwater Navigation Systems