# Developing a Flexible SPEAR3-Based Psychophysical Research Platform for Testing Cochlear Implant Users

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**Abstract**

An experimental psychophysical interface has been developed using Hearworks Pty Ltd's SPEAR3 research sound processor, which is compatible with Cochlear Corporation's Nucleus CI22 and CI24 implants. Modifications to the assembly code program file that resides in the SPEAR3 allow the parameters of a given stimulus to be updated on a trial-by-trial basis due to the responses given by a cochlear implant subject through a Visual Basic graphical user interface. Using a single program for the digital signal processor, this graphical user interface may be tailored to perform both traditional and original psychophysical experiments. The research sound processor also allows implementations of novel sound processing algorithms. Threshold and maximum comfort levels were measured with the SPEAR3, and one subject's levels were compared to those measured with the commercially available Nucleus Implant Communicator (NIC v2). No significant difference was found. Three cochlear implant subjects performed a rate discrimination task using the SPEAR3-based experimental interface, and the trends found in the resulting data imply that the SPEAR3-based experimental interface is functioning properly and may be used in the future for other psychophysical investigations.

## I. Introduction

Experimental interfaces for cochlear implants have allowed researchers to perform psychophysical experiments by directly manipulating the parameters of biphasic pulse trains on a trial-by-trial basis, implement common speech-processing algorithms, investigate the behavior of those algorithms through adjustments to user MAPs that specify stimulation mode, timing parameters, loudness growth function parameters and threshold and comfort levels, and also make changes to those algorithms such as adjusting filter parameters, changing the number of available channels and selecting the update rate [1], [2], [3], [4], [5]. Researchers have used these interfaces to gain a better understanding of the behavior of the cochlea in response to electrical stimulation, which has in turn led to the development of new speech-processing strategies that have resulted in improvements in speech recognition. These interfaces have been essential to the improvement of speech-processing strategies, but researchers were constrained by the framework of the interface provided by the manufacturer.

While other experimental interfaces offer control over the timing parameters and amplitude of each stimulus, along with the option of sending a predefined set of stimuli in succession, and also generally include current speech processing strategies, researchers do not typically have access to the programs within the speech processor of a cochlear implant (e.g., [2]). HearWorks has recently released the SHARP/SPEAR programming system (SPS), which allows either a SHARP or SPEAR3 (Sound Processor for Electrical and Acoustic Research, revision 3) sound processor to be connected directly to a personal computer for programming [6]. The SPS/SPEAR3 package has two real advantages over other research interfaces. The first advantage the SPS/SPEAR3 package has is that it gives developers access to the digital signal processor program file, and the ability to upload modified assembly code may be used to implement original psychophysical experiments and completely new sound processing algorithms. The second feature of this system stems from this ability to upload new strategies, and it is that it allows cochlear implant users to try new sound processing strategies in take home experiments, rather than being confined to an experimental environment. Daily use of a new strategy in familiar environments provides an opportunity to observe the possible effects of adaptation on a user's performance. In addition to access to the programs within the digital signal processor, the SPEAR3 has the ability to drive two Nucleus CI22 or CI24 implants for bilateral stimulation and may also be used in a multi-modal fashion, where an acoustic stimulus is also presented to take advantage of some remaining residual hearing [7]. For researchers who are primarily concerned with performing experiments that are confined to the laboratory, and especially those tasks that involve running speech or streaming longer sounds, Cochlear, Ltd.'s Nucleus Implant Communicator (NIC) is a good solution. While streaming is possible with the SPEAR3, serial port communication and limited data memory space prevent it from being the ideal device for this application.

HearWorks Pty Ltd offers the SPEAR3 Speech Processing system software at an additional cost. This software includes a configurable program file for the SPEAR3 and a graphical user interface (GUI) called Seed-Speak that enables researchers to manipulate the parameters of the SPEAK speech-processing strategy. Seed-Speak may also be used to obtain psychophysical data that is typically collected clinically via tasks including estimation, ranking, and loudness balancing [8]. However, for

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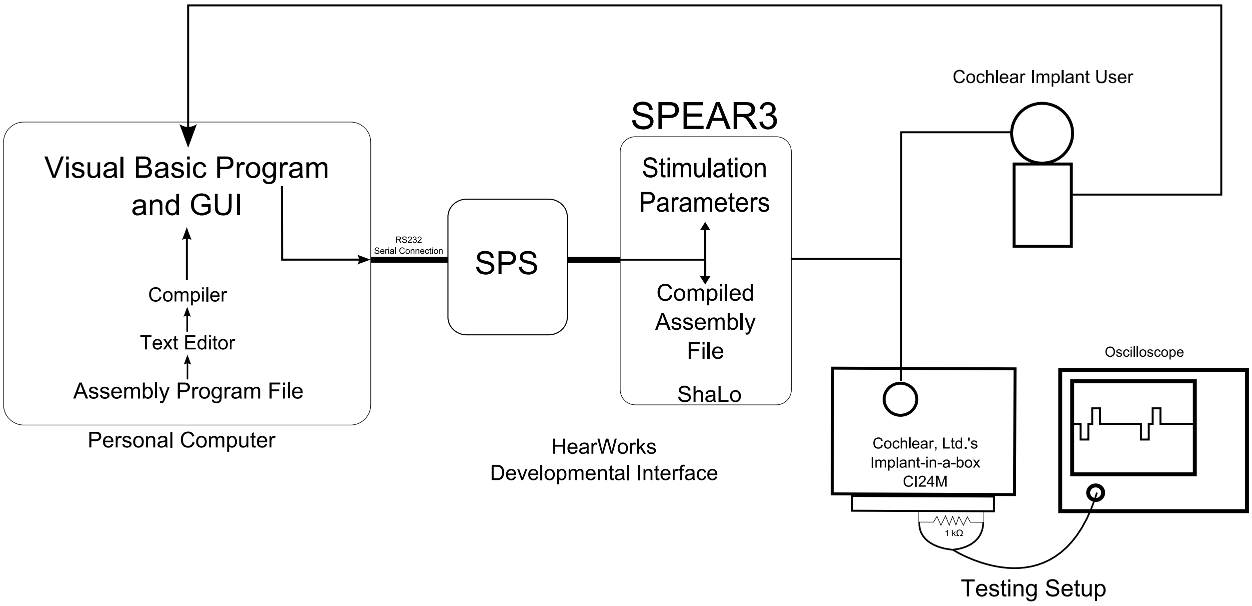


Fig. 1. Block diagram of the SPEAR3-based psychophysical research environment. A personal computer is connected to the SPEAR Programming System (SPS) through an RS232 serial connection, w hich then communicates with and controls the SPEAR3. Through this connection, HearWorks' Woomera software (see section II) or a custom Visual Basic program can be used to load compiled program files and other data, such as stimulation parameters, to the volatile memory spaces (X, Y, and P RAM). During a psychophysicalexperiment, a VB program sends the appropriate stimulation parameters to the SPEAR3, which then delivers the encoded and formatted stimuli to the implant user or to the Implant-in-a-Box for testing. The user provides a response based on the stimuli to a Visual Basic interface via the mouse or keyboard. This response is then used by the VB program to determine the next set of stimulation parameters that are sent to the SPEAR3.

researchers who wish to build a platform whose capabilities extend beyond those of the Seed-Speak software, HearWorks offers software development tools for the SPEAR3 [9]. One of the main advantages of this device is that in addition to implementing the simple psychophysics available in the manufacturer software, it is also possible to implement more complex psychophysics as well as new sound processing strategies. The software development tools include the necessary monitor/loader programs for the SPEAR3 processor, a dynamic linked library with functions for interfacing the SPS with the SPEAR3, example Visual Basic and assembly code, and documentation for the SPEAR3 and Motorola digital signal processor (DSP) [7].

The example assembly code provided with the software development tools does not provide the ability to update stimulus information at runtime (i.e., once the program is compiled) and must therefore be modified before performing psychophysical experiments in which stimulus data is updated on a trial-by-trial basis. The example Visual Basic code provided by HearWorks contains an example graphical user interface (GUI), but this interface is not compatible with the provided assembly code, nor does it include any psychophysical tasks. Given that the documentation provided by HearWorks supports development of graphical interfaces with Visual Basic, that language was used to develop a program and user interface that communicates with the sound processor via modified assembly code in order to perform psychophysical experiments.

In this technical note, the steps that were taken to implement basic psychophysical experiments for cochlear implants with the SPEAR3 will be discussed. Section II will address connecting to and communicating with the SPEAR3 hardware. Section III-A will address the modifications that were made to the assembly code that was provided. The Visual Basic framework and testing the output from the SPEAR3 will also be described. The details of psychophysical tasks such as threshold, maximum comfort level, loudness balancing and rate discrimination that were programmed in the SPEAR3-based environment that was developed will be covered in Section IV. In addition, data taken in those psychophysical tasks will be presented in Section V. The ability to obtain data from psychophysical tasks that is consistent with that found in the existing cochlear implant literature, along with a comparison of threshold and maximum comfort levels obtained with the SPEAR3 to those obtained with the NIC-2, serves as validation that stimuli are being presented as expected and that a SPEAR3-based environment may be used for future psychophysical research with Nucleus cochlear implants.

## II. Overview of the Hardware

The SPEAR3 is a research speech and sound processor made by HearWorks that is built on a 24-bit Motorola Digital Signal Processor (DSP56309) and permits the development of experimental psychophysics and sound processing algorithms. The SPEAR3 may be controlled by a host PC via the SPEAR Programming System (SPS). Both the SPEAR3 and SPS are provided by Cochlear Implant and Hearing Aid Innovation and HearWorks Pty Ltd. The SPS can communicate with any personal computer via an RS232C compatible serial port, and is connected to the SPS via a six-pin connector [10]. In order to operate at high bit rates, the manufacturers recommend that the serial port includes a hardware first-in, first-out (FIFO) buffer

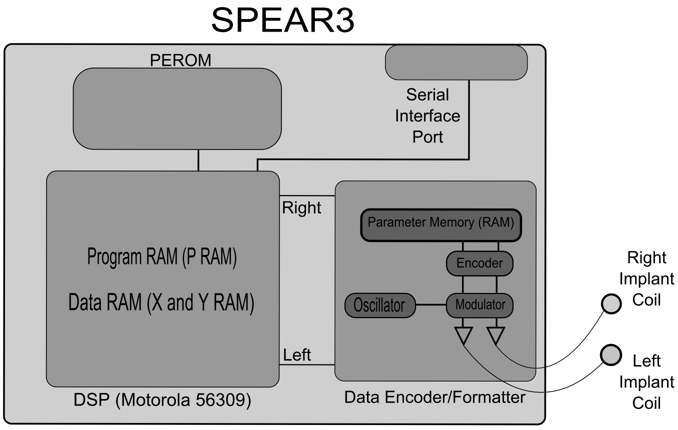


Fig. 2. Block diagram of the SPEAR3 hardware. The SPEAR3 is built on a Motorola DSP, may be programmed via a serial connection using the SPS, and also includes a data encoder/formatter (DEF) that is used to drive bilateral cochlear implants made by Cochlear Corporation.

[11]. A block diagram of the experimental SPS testing interface that was implemented with a SPEAR3 sound processor can be found in Figure 1. The testing portion of the block diagram was included in the experimental setup to examine stimuli prior to experimental testing with cochlear implant subjects and is discussed in Section III-C1.

Access to the assembly code program file that is used to operate the Motorola DSP56309 processor is the main advantage of the SPEAR3, and in order to perform such operations as loading and saving compiled programs and accessing processor memory locations, a loader/debugger program is needed. HearWorks provides the Woomera loader/debugger software package for this purpose [12]. This software package includes 1) a graphical interface for uploading programs into the processor and managing memory content, and 2) the ShaLo monitor/loader program, which resides in the non-volatile PEROM (Programmable and Erasable Read Only Memory) and adds the functionality to the sound processor of storing additional data in the PEROM and transferring data into the internal, volatile program memory space (P RAM) and data memory spaces (X and Y RAM) [12]. The program memory space (P RAM) is used to temporarily store compiled program files that are either used in psychophysical experiments or are complete speech processing strategies. The data memory spaces (X and Y RAM) may be used to store stimulation parameters while running psychophysical experiments, during the operation of a sound processing strategy, or in any other situation that may require storage in volatile memory. The SPEAR3 also includes a Data Encoder Formatter (DEF) that takes stimulus parameters that have been transferred from the memory of the processor into the DEF memory and encodes them into a pulse modulated radio frequency (RF) signal, which is then transmitted to a cochlear implant [6]. A block diagram of the SPEAR3 hardware can be found in Figure 2.

### *A. Compatibility with Implants and Data Protocols*

The SPEAR3 is compatible with Cochlear, Ltd.'s Nucleus CI22 and CI24 implants. These implants are limited to sequential modes of stimulation including monopolar, bipolar and common ground and are not capable of simultaneously stimulating multiple electrodes or operating in a tripolar stimulation mode. Note that while the SPEAR3 is compatible with the Freedom (CI24RE) Implant in the Monopolar 1+2 (MP1+2) mode of stimulation, the value used to indicate that the mode of stimulation parameter is MP1+2 must be set to reflect the specific use of a CI24RE, which is different than the parameter value that is set to indicate earlier versions of the CI24 (Personal communication: Colin Irwin, Chris van den Honert, Cochlear Corporation and Andrew Vandali, Cooperative Research Centre for Cochlear Implant and Hearing Aid Innovation).

Two protocols are available for data transfer from the processor to the implant, the expanded protocol and the embedded protocol. Each protocol is responsible for the data that is sent to to the implant via the DEF, which includes electrode, mode of stimulation, amplitude, interphase gap, interframe gap, and phase width information. Under the expanded protocol, parameter values are coded by the number of RF cycles; and therefore, the stimulation rate is dependent on the aforementioned parameters. In contrast, using the embedded data protocol gives the DEF the ability to send encrypted data for the next stimulus during the current stimulus' pulse widths, and therefore the embedded protocol has the advantage of rate being independent of the values of the parameters that are being transmitted. The CI22 is controlled using the expanded protocol, and the CI24 may be controlled using either the expanded or embedded encoding protocol. While the SPEAR3 is capable of both the embedded and expanded protocol, the embedded data protocol permits researchers to work with subjects who have the newer CI24 implant, can operate in narrow pulse width mode, has a simpler set of stimulus parameters, and makes the SPEAR3 maximum stimulation rate of 15.6 kpps achievable [13].

### B. Stimuli

Standard stimulus parameters for a biphasic pulse include, mode of stimulation, active electrode, reference electrode, pulse width ($\mu$s), stimulus amplitude (current steps), interphase gap ($\mu$s), and interframe gap ($\mu$s), which is the time between the second phase of the stimulus and the onset of the following stimulus. The SPEAR3 is capable of operating in the common ground, bipolar, or monopolar mode of stimulation. The active electrode may be any properly functioning intracochlear electrode in the implant user's array. The reference electrode is determined by the stimulation mode. The amplitude is expressed in current steps and may take any value between 0 and 255. The CI24 uses the following current law [13]:

$$I = a175^{\left(\frac{n}{255}\right)} \tag{1}$$

where $I$ is the applied peak current, $a$=10 $\mu$A, and n = 0...255 (current steps). The width of the anodic and cathodic phase should be equal to ensure a charge balanced stimulus [14]. The timing parameters (i.e., phase width, interphase gap, and interframe gap) are specified in cycles of 0.2 $\mu$s, which is the period of the 5 MHz carrier used in the radio frequency (RF) link in a Nucleus CI24 [9]. The availability of two bytes of memory allows up to 65,535 cycles to be assigned to a given timing parameter, which means that the maximum possible pulse width and interphase gap are equivalent to approximately 13 milliseconds. The minimum pulse width is 25 $\mu$s. The minimum interphase gap is 7 $\mu$s. The interframe gap is the time between the second phase of a stimulus and the onset of the first phase of the subsequent stimulus. The interframe gap is calculated based on the desired pulse rate and other timing parameters, and this calculation is presented in Section III-B. The interframe gap is also allocated two bytes in memory, and so it has the same upper limit of 13 milliseconds in duration [9].

## III. Overview of the Software

A dynamic linked library (DLL) of functions has been provided by HearWorks in order to facilitate communication between the host PC and the SPEAR3 via the SPS. These functions require the programmer to first load the ShaLo software loader into the SPEAR3. This can be done using HearWorks' Woomera, and only needs to be done once in the lifetime of the sound processor [15]. The functions provided in the DLL include those needed to establish a connection with the SPS through the computer's serial communication port along with a variety of memory related functions.

### A. Modifying the Assembly Code

Once a connection has been established with the SPEAR3, a compiled assembly code file (.lod file) must be loaded into the processor memory to interpret incoming data. This file can be loaded with Woomera, but using a separate stand-alone GUI for this operation is not practical for psychophysical tasks. Instead, the Visual Basic function *SpearLoadProgram* can be integrated into a psychophysical program. An example assembly file that allows the programmer to load a static set of stimulation parameters into the program memory of the sound processor is provided with the SPEAR3. In the example assembly code provided by HearWorks, a table containing blocks of stimulus data is stored in the program memory. Each block defines the parameters needed to create a single pulse, and up to 46 sequential sets of stimulus parameters may be stored in the 512 bytes of the encoder RAM [9]. At runtime, the assembly code that was provided transfers stimulus blocks from the table stored in the program memory to the DEF, sends the stimuli to the implant (up to 46), and repeats this loop indefinitely while the loaded program is running. The preloaded parameters determine the stimulus sent during each iteration, which is an apical to basal sweep of the electrode array in the example table, but may again be up to 46 blocks or 46 sequential pulses.

For psychophysical applications, it is necessary to be able to update the stimulation parameters on demand, i.e. trial to trial. This requires a modification to the original assembly code provided by HearWorks. The modified assembly code contains a subroutine that reads stimulus parameters from the data memory (X RAM) instead of retrieving them from a preloaded table stored in the program memory (P RAM). Using the function *SpearWriteMemory*, it is possible to send values directly to the internal memory. Along with pulse parameter values, the number of desired pulses ($n$) is also written to X RAM, resulting in the ability to present a pulse train of a given duration. Following the presentation of $n$ active pulses, null frames are sent indefinitely to the implant to avoid having to send power-up pulses at the beginning of each block of stimuli. Power up pulses are required to ensure that the soft turn-on period has elapsed, allowing the appropriate capacitor to fully charge within the implant [16]. During a null frame in bipolar or common ground mode, all intracochlear electrodes are shorted to ground and extracochlear electrodes are open circuited. In monopolar mode, null frames may be mimicked by sending a minimum amplitude stimulus between the extracochlear electrodes and shorting all intracochlear electrodes to ground [13]. Once a complete set of stimulation parameters has been transferred to the X RAM, a flag is set by a Visual Basic program, and the new active stimulus parameters are transferred to the DEF. Additionally, wait states occur in the main program file until the encoder is free to ensure that new parameters are transferred without interrupting the DEF, and the encoder is then started again. The result of this series of actions is that the modified stimuli are sent to the cochlear implant. A flow chart of the modified assembly program file is shown in Figure 3.

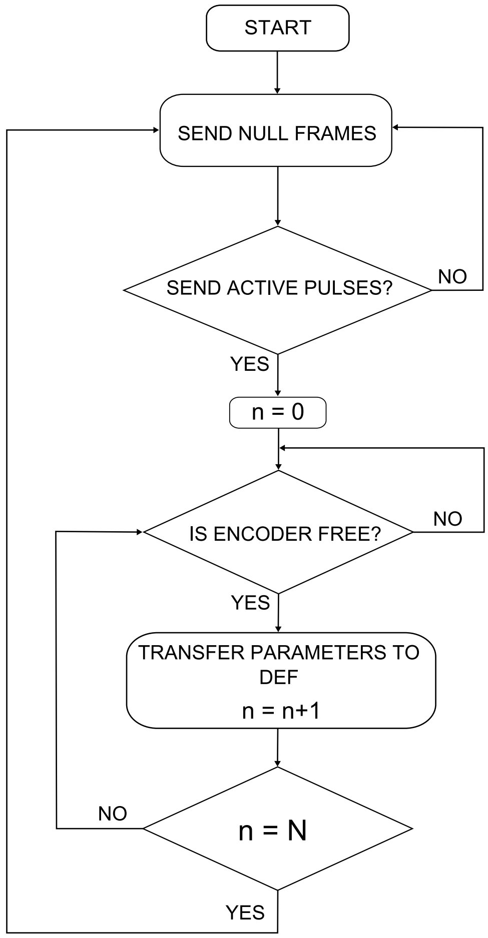


Fig. 3. Flow chart for the modified assembly program file used to implement psychophysical experiments. Null frames are delivered to the implant until the number of active pulses to be sent (*N*) and active pulse parameters have been transferred to the SPEAR3 data memory, and a flag is set by a Visual Basic program indicating that active pulses should be delivered in place of null frames. The main program file includes a subroutine to ensure that the encoder is free before transferring active pulse parameters from the data memory to the DEF memory. This process is repeated for *N* pulses, after which null frames are sent indefinitely to keep the implant powered up.

## *B. Using Visual Basic to Create a Graphical Interface*

The example assembly code was modified in such a way that it would allow stimulation parameters to be modified at runtime. One way to modify stimulus parameters is to call functions from the SPS library with a VB program. A Visual Basic graphical interface facilitates loading cochlear implant parameters such as implant type and stimulation mode, stimulus parameters such as pulse width, interphase gap and pulse rate and experimental parameters such as stimulation duration and interstimulus interval. This VB interface must also serve as means of indicating the presence or absence of stimuli to the cochlear implant user and take user input that is then used by a VB program to determine the next set of stimuli. Figures 4 and 5 contain examples from the Visual Basic interface used in the rate discrimination task in this paper. The figure includes two windows used by the moderator, one which contains stimulation parameters and one that contains experimental parameters. This figure also contains an example of a window that would be used during a psychophysical experiment to communicate with the subject. Electrode discrimination and paired comparison pitch ranking are examples of other psychophysical experiments that have been implemented within this framework but are not included in this paper.

Some mathematical manipulations are necessary to convert standard stimulus parameters used by experimenters to those needed by the SPEAR3, and these calculations were implemented in the Visual Basic program used for the experiments reported in the present study. The pulse width (PW), interphase gap (IPG) and interframe gap (IFG) are each allocated two bytes of memory. These timing parameters are first converted to total number of cycles of the 5 MHz carrier, and then it is necessary to perform separate high-byte and low-byte calculations for each parameter to accomodate the byte-wide DEF RAM. The calculations found in equations 2 through 12 convert the timing parameters from units of time to the two-byte representations of the corresponding number of required RF cycles. Here, $\lfloor \ \rfloor$ indicates the floor function, $PW$ indicates pulse width, $IPG$ indicates interphase gap, $IFG$ indicates interframe gap, $LB$ indicates low-byte, and $HB$ indicates high-byte.

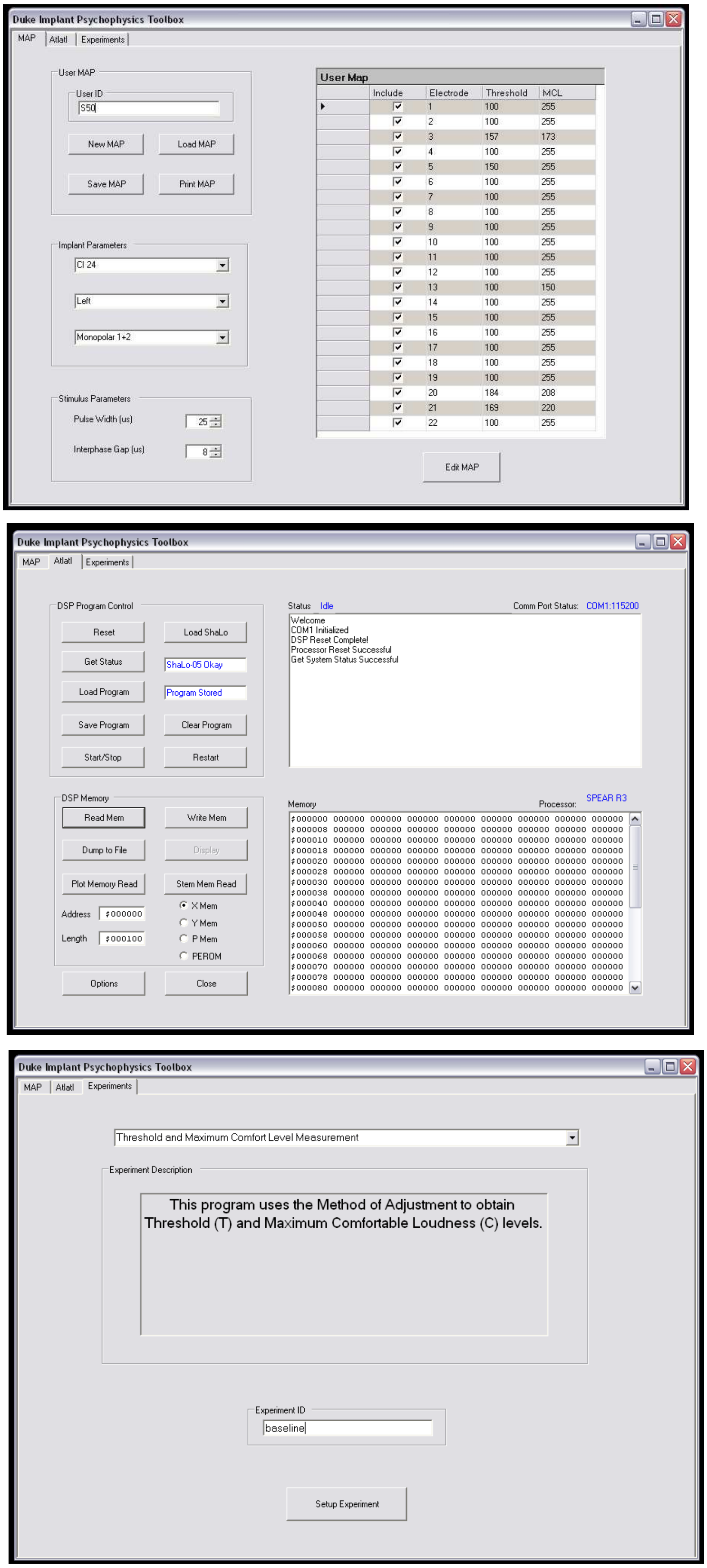


Fig. 4. Duke Implant Psychophysics Toolbox (DIPT). The top window shown here is the MAP tab and allows user maps to be created and modified. A previously created user map is always loaded as read-only and may be edited by selecting the Edit MAP button. This is to eliminate accidental changes to user threshold and maximum comfort level values. The middle window is the Atlatl tab, which is the DIPT version of Woomera. This tab allows the host PC to connect to the SPEAR3 via the SPS, load programs, monitor the status of the SPEAR3, and manage the memory contents of the SPEAR3 as well. The bottom window shown here is the Experiments tab. This tab contains a drop-down list of all available psychophysical experiments, and a description is provided when an experiment is selected. An experiment ID is also entered here. Cicking the Setup Experiment button will open a new window like the one shown in Figure 5 that allows the moderator to enter specific information about the stimuli and experimental paradigm.

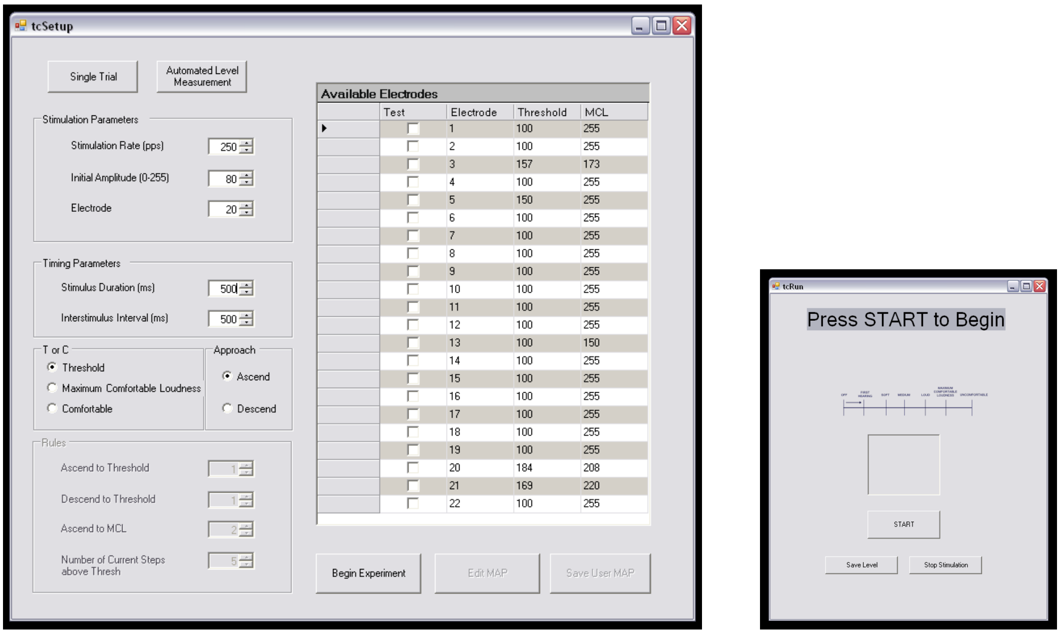


Fig. 5. DIPT Setup and Run windows for Threshold and Maximum Comfort Level measurement. The left window is intended for use by the moderator and includes the subject's available electrodes, previously associated T and MCL values, and all of the relevant parameters for a particular experiment. The right window contains the interface provided to the subject. Given that this experiment is a measurement of T and MCL values via the Method of Adjustment, the subject has access to a Start button to begin the experiment, a Save Level button to store the present stimulus amplitude, a Stop Stimulation button in the case of an undesired stimulus, instructions and a visual aid to indicate the present task (i.e., First Hearing or Threshold), and a box that will illuminate to indicate the presence of a stimulus. This figure is intended to be illustrative, as each experiment has a unique Setup and Run window with relevant parameters for the moderator and visual cues for the subject, respectively. All experiment Run windows have a Stop Stimulation button for the safety of the subject.

$$
\begin{aligned}
PW(\text{cycles}) &= 5 * [PW(\mu s) - 25] && (2)\\
PW(HB) &= \left\lfloor \frac{PW(\text{cycles})}{256} \right\rfloor && (3)\\
PW(LB) &= \lfloor PW(\text{cycles}) - PW(HB) * 256 \rfloor && (4)\\
& && (5)\\
IPG(\text{cycles}) &= 5 * [IPG(\mu s) - 7] && (6)\\
IPG(HB) &= \left\lfloor \frac{IPG(\text{cycles})}{256} \right\rfloor && (7)\\
IPG(LB) &= \lfloor IPG(\text{cycles}) - IPG(HB) * 256 \rfloor && (8)\\
& && (9)\\
IFG(\text{cycles}) &= 5 * \left[ \frac{10^6}{stimulation\ rate(pps)} - [IPG(\mu s) + 2 * PW(\mu s)] - 7 \right] && (10)\\
IFG(HB) &= \left\lfloor \frac{IFG(\text{cycles})}{256} \right\rfloor && (11)\\
IFG(LB) &= \lfloor IFG(\text{cycles}) - IFG(HB) * 256 \rfloor && (12)
\end{aligned}
$$

After the timing parameters have been converted to number of cycles, the VB program arranges the data into stimulus blocks that are then sent to the X RAM via the *SpearWriteMemory* function. The Visual Basic GUI can take user input in the form of a mouse click or key press, and this information can be used to determine how stimuli should change from trial-to-trial using, for example, the method-of-adjustment [17] or an adaptive procedure [18]. Stimulus duration is defined by the pulse rate and the number of pulses sent, and the interstimulus interval may be controlled by puasing the VB program while the DEF is sending null frames to the implant. Data collected throughout experiments may be stored by the VB program in a variety of formats including extensible markup language (.xml) files and text (.txt) files. It is important to note that the maximum stimulation rate of 15.6 kpps is only achievable when sending stimuli whose parameters are already loaded into the X RAM. When writing data to the X RAM, a temporary break in the execution of the assembly program will occur. For this reason, it is recommended that parameters be updated during an interstimulus interval or at some other time when no stimulus is being presented.

A compiled version of the modified assembly code file will be made available upon request, along with an open source version of the Visual Basic program and user interface. This code is intended to enable the researcher to develop unique psychophysical experiments within this framework, and all stimuli should be tested thoroughly before performing any tests with human subjects.

### C. Safety Precautions

*1) Testing Setup:* In order to test the SPEAR3 output prior to implementing psychophysical experiments and using human subjects, Cochlear, Ltd.'s "Implant-in-a-box" was utilized. The "Implant-in-a-box" used for testing contained a Nucleus CI24M cochlear implant with a female DB25-pin connector that functions as the output of the device and allows measurement of interelectrode potential. The first 22 pins of the DB25 act as electrodes 1-22. Pin 23 is open, and pins 24 and 25 are a ball electrode and a plate electrode, respectively. These two pins are used as ground in the different monopolar modes of stimulation (Personal communication: Phil Segel, Cochlear Corporation).

The SPEAR3 sound processor has either one or two coils (for unilateral or bilateral stimulation) that would normally be held against the scalp of a cochlear implant user through the use of magnets, but during testing, the coil is instead held against the "Implant-in-a-box." To test the operation of the SPS and the output from the SPEAR3, a simple stimulus with fixed parameters was sent from the SPEAR3 to the Implant-in-a-box through the coil. The implant decodes the transmitted RF signal, and the output may be viewed using an oscilloscope. A 1 kΩ load resistance between the stimulating and ground electrode was used to mimic the resistive properties of the cochlea. A Tektronix TDS 210 two channel digital real-time oscilloscope was used to view the output waveforms from the CI24. This test setup allowed the validation of all stimulation parameters including rate, pulse width, interphase gap, amplitude, and mode of stimulation.

*2) Software Safety Checks:* The SPEAR3 includes built-in safety checks such as monitoring both the battery and the state of the DEF, but it is necessary to take further precautions to ensure the safety of subjects. In the graphical interface, inputs for the duration of each pulse and the interphase gap are limited by their minimum and maximum possible values as defined by the allocation of two-bytes for each parameter, and the stimulation rate is limited by the duration of the pulse widths, interphase gap, and the allocation of two-bytes for the interframe gap (see equations 10 through 12). Before running any experiments or implementing sound processing algorithms, threshold and maximum comfortable levels should be measured at all appropriate combinations of pulse width, interphase gap, stimulation rate, and mode of stimulation. Once these values are obtained, the stimulus amplitude should be limited by the user's threshold and MCL values. In addition to limiting the value of each parameter within the program, each GUI contains a "Stop Stimulation" button that allows the user to immediately stop any undesired stimulus. Given that duration is defined by the number of pulses to be delivered, total stimulus duration is limited by the maximum integer value that can be stored in the Motorola 24-bit memory location $(2^{23} pulses)$. Actual duration will depend on the stimulation rate and other pulse parameters. The VB program also includes a series of checks, redundant with the limitations imposed in the interface, to make sure that all parameters are both defined and fall within the appropriate limits before the program in the SPEAR3 is allowed to run.

## IV. Experimental Methods

Three psychophysical experiments were implemented in this study to verify that reasonable psychophysical results were being obtained with the research interface. Using the SPEAR3, threshold and maximum comfortable loudness (MCL) values were measured for three electrodes at the apical, middle, and basal locations of the cochlea in three subjects. These measurements were repeated with the commercially available NIC v2 for one subject. Using the threshold and MCL values obtained with SPEAR3 to determine reference amplitudes (seventy-five percent of the dynamic range), a loudness balancing procedure was implemented on single electrodes using different stimulation rates. The results of the loudness balancing procedure were then used to reduce loudness cues in a two-down, one-up, two-interval, forced-choice, adaptive procedure [18], where the goal was to find the subject's pulse rate difference limens (PRDL) on each of the three electrodes tested. The main goal when performing these three procedures was to verify the proper functioning of the SPS and SPEAR3 hardware and all of the accompanying Visual Basic and assembly language code needed to implement psychophysical experiments in cochlear implants.

### A. Subjects

Three post-lingually deafened subjects participated in this study. All three subjects were implanted with Nucleus CI24 multichannel implants. Subject S2 is a 71-year-old female who has been using her device for over five years. Subject S3 is a 69-year-old male who has been using his device for approximately five years, and subject S4 is an 18-year-old male who has been using his device for over five years. An informed consent, approved by The Duke University Institutional Review Board, was obtained, and the subjects were compensated for their time.

### B. Stimuli

The stimuli used to determine threshold and maximum comfortable loudness levels, and in implementing the loudness balancing procedure and the stimulation rate discrimination task, were 500-ms pulse trains of biphasic rectangular pulses, presented with a 500-ms interstimulus interval. Pulse width, interphase gap and stimulation mode were determined by the user's clinical MAP. All three subjects used a monopolar 1+2 stimulation mode with a pulse width of 25 $\mu$s and an interphase gap of 8 $\mu$s. Stimulus amplitude and pulse rate varied from trial to trial in both the loudness balancing and rate discrimination tasks. Due to the value of a constant used in the initial method of calculation, all reported parameter values are approximations of the actual parameters. One apical, one middle and one basal electrode were used for all subjects. Specifically, electrodes 20, 12 and 4 were used in all experiments for all subjects, where 1 is the most basal electrode.

The SPEAR3 research speech processor, was used to present all stimuli to the subject. A MicronPC computer with an Intel Pentium III processor was used to control the SPEAR3 and the Visual Basic program that includes the psychophysical user interface. In all tasks, stimuli were accompanied by visual cues provided via a color CRT monitor. In the rate discrimination task, correct and incorrect response feedback was also provided.

### C. Procedures

*1) Threshold and maximum comfortable loudness:* Before implementing any other psychophysical tasks, it is necessary to ensure that all stimuli will be presented above the user's threshold and below the maximum comfortable loudness (MCL) [19]. These values are unique for each subject and each electrode, and therefore these measurements were taken for all three of the electrodes used during the course of this study. The stimulation rate was fixed at approximately 250 pulses per second (pps).

The method of adjustment (MOA), which is commonly used clinically, was used to determine threshold and MCL on an apical, middle and basal electrode [20]. The threshold was measured with an ascending and descending approach, and the MCL was only measured from below. The subject was instructed to press the up and down arrow keys on a standard keyboard to increase and decrease the stimulation amplitude, respectively. The stimulus level was first set at a value below the threshold of detection, and the subject was instructed to press the up arrow until the stimulus could first be heard. This task was repeated three times, and then the stimulus was initialized at a value above the threshold. Subjects were instructed to use the down arrow to decrease the amplitude of the stimulus until it became unperceivable. The descending task was also repeated three times. The amplitude of the stimulus was then set to a value slightly higher than the threshold of detection, and the subjects were instructed to increase the stimulus amplitude using the up arrow until the volume was loud but tolerable for a short period of time. This was repeated three times to determine the MCL. Had subjects adjusted the volume beyond a comfortable level, the "Stop Stimulation" button was available to immediately prevent stimuli from being sent. The entire procedure was repeated on all three of the electrodes used in these experiments. The six measurements (3 ascending, 3 descending) were averaged to calculate threshold, and the three measurements were averaged to estimate MCL. One subject repeatesd this procedure with NIC v2 to verify that values obtained with the SPEAR3 matched those obtained with another commercially available device.

*2) Loudness balancing procedure:* It has been shown that loudness may increase with an increase in stimulus rate [21], [22]. In order to reduce the possibility of loudness cues in the pulse rate discrimination task, a loudness balancing procedure was implemented, again using the method of adjustment. Two intervals were presented in an alternating fashion, separated by a 500-ms interstimulus interval, and each was accompanied with a visual cue. The first of the two stimuli was a fixed-level, reference interval, and the second stimulus was presented at a fixed rate that was approximately 100 pps higher than the reference interval and had an adjustable amplitude. Here, the term interval refers to a stimulus containing a single pulse train. Subjects were asked to use the up and down arrow keys on a keyboard to adjust the amplitude of the second stimulus until its loudness was equal to that of the reference stimulus. Reference stimulation rates included 100, 200, 300 and 400 pps, and target stimulation rates included 200, 300, 400 and 500 pps, respectively. The reference amplitude for the lowest stimulation rate was set to 75 percent of the dynamic range for the electrode under test, and rates were presented from lowest to highest. The target stimulus was presented three times with an initial amplitude below the reference stimulus and three times with an initial amplitude above the reference stimulus. The six resulting loudness balanced values were averaged to determine the amplitude of the next reference rate, which was previously the target rate. The average loudness balanced amplitudes were used in the subsequent rate discrimination task. Although this method results in loudness balance values that are dependent on previous measurements, [23] suggests that such methods do not attribute to increases in error greater than those observed with independent measurements.

*3) Rate discrimination task:* An adaptive, two-interval, forced choice procedure [18] was implemented to determine the smallest differences in stimulation rate that were discriminable to the subject at various base rates. Flanking cues were used in this procedure, i.e. four intervals were presented sequentially with a 500-ms interstimulus interval, and the first and last interval were always reference intervals presented at the base rate used to calculate the reported difference limen. Three of the four stimuli were presented as reference intervals, all with a fixed stimulation rate, and either the second or third stimulus in the set of four was randomly selected as the target stimulus. The target stimulus had a higher rate than the reference stimulus and an amplitude that was determined based on the previous loudness balancing procedure. All amplitudes were roved by one standard deviation of the loudness balance data. The adaptation of the target stimulation rate followed the rules of the

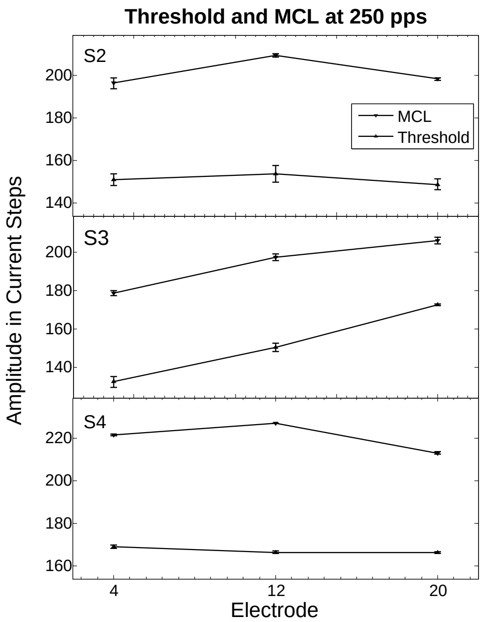


Fig. 6. Threshold and MCL for subjects S2, S3 and S4. The x-axis plots the electrode number from most basal to most apical. The y-axis plots the average amplitude in current steps. Threshold values are shown with triangular symbols pointing up, and MCL values are shown with triangular symbols pointing down. Error bars indicate the $\pm$ standard errors.

2-down, 1-up procedure described in [18]. A total of 12 reversals or 60 trials was required to complete the task. Subjects were instructed to select the different stimulus by pressing either '1' or '2' on the number pad of the keyboard, indicating interval 1, the second stimulus, or interval 2, the third stimulus, respectively. Visual feedback was given such that a correct response was indicated by changing the color of the correct interval to green, and an incorrect response was indicated by changing the color of the correct interval to red. The last 8 reversals were averaged to determine the DL for each reference pulse rate, and in the cases where the subject did not reach 8 reversals, the last $n$ reversals were averaged, where $n$ is the largest even number of reversals present in the task under consideration. Reference pulse rates included 100, 200, 300 and 400 pps. The corresponding initial target pulse rates were 200, 300, 450 and 600 pps. An adaptive procedure was implemented one time for each reference rate on each electrode [18].

## V. Experimental Results

### A. Threshold and maximum comfortable loudness

Results of the threshold and MCL task for subjects S2, S3 and S4 are shown in Figure 6. On all three electrodes in all three subjects, the experimental threshold was lower than the experimental MCL. The experimental dynamic range was typically smaller than the clinical dynamic range; however, this may have been due to a tendency to be more conservative in a new, experimental setting. The relatively low rate of stimulation at which threshold and MCL values were collected may offer another possible explanation for the reduction in dynamic range with respect user's clinical maps [24].

Subject S2 repeated the threshold and MCL task with the NIC v2 device, provided by Cochlear, Ltd. Measurements taken with both the SPEAR3 and the NIC v2 are shown in Figure 7. Errors bar represent the $\pm$ standard errors, and the difference between the means of the measurements taken with the two devices was not statistically significant ($t$-test, $P < 0.01$).

### B. Loudness balancing procedure

Loudness balancing is necessary to reduce loudness cues in other tasks. It has been shown [21], [22] that an increase in stimulation rate may result in an increase in perceived loudness. Therefore, if stimuli of different rates are presented to the same electrode, it is assumed that the higher rate may be perceived as louder. This difference could be a cue to find the "different" stimulus in a rate discrimination task that is obviously not related to rate differences. To eliminate the loudness cues from a rate discrimination task, a loudness balancing task may be implemented so that stimuli of varying rates but equal duration are perceived to have the same loudness. Loudness balancing results on electrodes four, twelve and twenty for subjects S2, S3 and S4, respectively, can be seen in Figure 8. The trends of decreasing stimulation amplitude with increasing pulse rate and decreased separation between reference and target amplitudes with increased stimulation rate are present on electrode 4 in subject S2 [21], [22]. The loudness balance results for subjects S3 and S4 contained no statistically significant difference between amplitude values at stimulation rates from 200-500 pps ($t$-test, $P < 0.01$). Additionally, loudness balancing results across all three subjects reflect the large amount of variability seen in the literature.

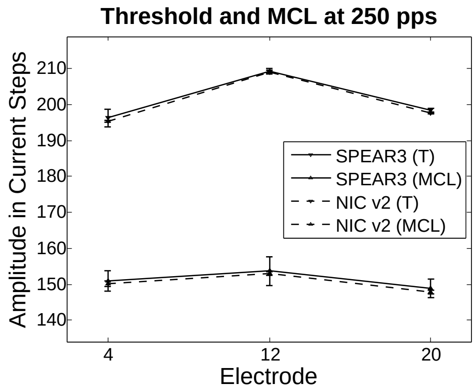


Fig. 7. Threshold and MCL levels for subject S2 taken with the SPEAR3 and NIC v2. The x-axis plots the electrode number from most basal to most apical. The y-axis plots the average amplitude in current steps. SPEAR3 measurements are shown with a solid line, and NIC v2 measurements are shown with a dashed line. Threshold values are shown with triangular symbols pointing up, and MCL values are shown with triangular symbols pointing down. Error bars indicate the $\pm$ standard errors. Note that there is no statistical difference between the means of the measurements taken with the two devices ($t$-test, ($P < 0.01$).

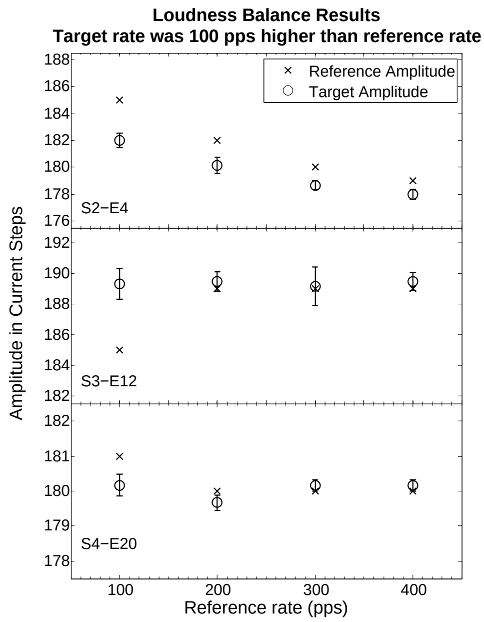


Fig. 8. Loudness balancing results for S2's electrode 4, S3's electrode 12 and S4's electrode 20. The x-axis plots the reference rate. The y-axis plots the average amplitude in current steps. Average amplitude values for a reference rate are shown with an "x." Average amplitude values for a target rate that is 100 pps higher than the corresponding reference rate are shown with an "o". Error bars indicate the $\pm$ standard errors.

### *C. Rate discrimination task*

The pulse rate discrimination results for all subjects are shown in Figure 9. It is well documented that multi-channel cochlear implant users do well on rate discrimination tasks up to approximately 300 pps, at which point there is usually a dramatic decrease in performance [19], [25], [26], [27], [28], [29]. This trend was observed for all three of the subjects, for all tested electrodes. All three subjects demonstrated slightly better discrimination at a reference stimulation rate of 200 pps when compared with a reference stimulation rate of 100 pps on at least one electrode. This improved detection of the target stimulus at 200 pps may be due to the presence of a loudness cue that resulted from insufficient loudness roving. It is also possible that quality of the stimuli at 200 pps may result in a more salient pitch percept than that elicited at 100 pps [30], which may have contributed to decreased pulse rate difference limens at 200 pps. Other than the aforementioned behavior, affecting the monotonicity of the pulse rate discrimination difference limens with increasing rate, the results of this task are consistent with results in the literature [19], [25], [26], [27], [28], [29].

## VI. Summary

The three psychophysical tests implemented resulted in data consistent with those in the large volume of existing cochlear implant literature. Additionally, the comparison of threshold and MCL values to those obtained with the NIC v2 serve as

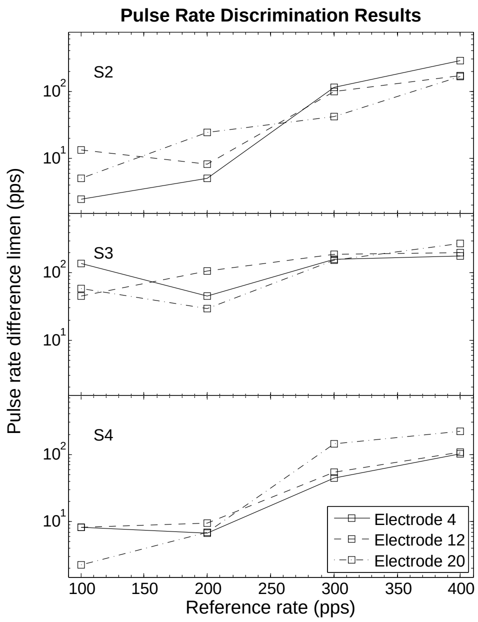


Fig. 9. Rate discrimination results for subjects S2, S3 and S4. The x-axis plots the reference rate. The y-axis plots the difference limen (DL) in pulses per second. Average DL values for a reference rate are shown with a square. The solid line corresponds to electrode 4, the dashed line corresponds to electrode 12 and the dash-dot line corresponds to electrode 20.

further validation that the SPEAR3-based research interface is functioning properly. In spite of the variability across subjects, some general trends can be observed in the literature. For example, the threshold values in this study were always smaller than the maximum comfortable loudness levels for all subjects on all electrodes tested, and subjects expressed no unfamiliarity or discomfort with the stimuli. The loudness balance results also demonstrated that a change in pulse rate is often accompanied by a change in perceived loudness. Using the loudness balancing results to avoid loudness cues in a two-down, one-up, two-interval, forced-choice, adaptive procedure generally provided monotonically increasing rate difference limens with increasing pulse rate. The monotonicity observed in these curves, with the exception of some results for a reference rate of 200 pps, follows trends found in the cochlear implant literature [19], [25], [26], [27], [28], [29].

Ultimately, the results of the these three psychophysical experiments served the original purpose of validating the proper function of the SPS and SPEAR3-based psychophysical research tool that has been developed. All procedures were carefully tested using the Implant-in-a-Box and oscilloscope, and all stimuli were consistent trial-to-trial with the parameters defining them. No adverse incidents were observed, and subjects expressed no concern with respect to the way stimuli sounded. The similarity of the trends found in the results of these common tasks to those in the literature, and to those obtained with the NIC v2, demonstrates the ability to accurately use the SPEAR3 for the implementation of traditional psychophysical tasks. In addition, the verification of the stimuli provided by the SPEAR3 means that stimulation parameters may be changed to perform more general psychophysical experiments. The availability of this new research interface, which offers the researcher more control over the digital signal processor, could play an important role in the continuing improvement in cochlear implant sound processing strategies.

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