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Speech Processors for Auditory Prostheses

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I. Introduction

The purpose of this project is to design and evaluate speech processors for implantable auditory prostheses. Ideally, the processors will extract (or preserve) from speech those parameters that are essential for intelligibility and then appropriately represent these parameters for electrical stimulation of the auditory nerve or central auditory structures. Work in the present quarter included the following:

1. Analysis of results from studies with *virtual channel interleaved sampling* (VCIS) processors, including a factor analysis of results from studies of VCIS processors with reduced numbers of electrodes.
2. Preliminary evaluation of variations in *continuous interleaved sampling* (CIS) processors, including (a) the use of an adjustable gain at the output of each envelope detector to normalize speech intensities across channels, and (b) the use of a noninstantaneous compressor at the output of each envelope detector to mimic crudely the noninstantaneous compression that occurs in normal hearing at the inner hair cells and at the synaptic junctions between IHCs and single fibers of the auditory nerve. Tests were conducted primarily with Ineraid subject SR2.
3. Development of new DSP56001 code to implement these variations with the laboratory speech processor system.
4. Development of strategies to improve the representation of IHC/synaptic function for inclusion in new speech processor designs.
5. Preparation for studies with two patients implanted with the new Auditory Brainstem Implant, jointly developed by the House Ear Institute and Cochlear Corporation. The new implant includes an electrode array with eight surface contacts. The two patients are able to rank at least a subset of those electrodes on the basis of pitch percepts. This ability has not been demonstrated in any of the prior ABI patients, who used a different type of electrode array. The present electrode array is interfaced with the standard transcutaneous transmission system used in the Nucleus cochlear implant device. Work in this quarter included modification of our existing TTS driver for the Nucleus implant so that it now can accept stimulus instructions from our new DSP56001 speech processor system (as opposed to the old TMS320-based system originally used with the TTS driver). Studies with the two patients will include evaluations of CIS processors, whose function depends on clear differences in perceived pitch across electrode channels.
6. Continued studies of the representations of complex tones by CIS and VCIS processors. These studies were conducted with Ineraid subject SR2.
7. Continued analysis of data from prior and current studies, to evaluate effects of single parameter changes on the performance of CIS processors.
8. Presentation of project results in invited lectures at the *1993 Conference on Implantable Auditory Prostheses*, held in Smithfield, RI, July 11-15.
9. Continued preparation of manuscripts for publication.

In this report we present results from the studies with complex tones (point 6 above). Work indicated in points 1, 2, 4, 5 and 7 above will be described in future reports.

II. Representation of Complex Tones by Sound Processors for Implanted Auditory Prostheses

Background

Crudely mimicking functions of normal acoustic hearing, multichannel sound processors for implanted auditory prostheses seek to convey sound spectra in two distinct ways -- place information and periodicity information.

Place information is conveyed by selectively stimulating groups of neurons associated with different locations along the organ of Corti and, hence, different sensations of pitch. The effectiveness of this approach for conveying spectral information depends on identifying perceptually distinct channels of stimulation, which may correspond to stimulation with different physical electrodes or different combinations of electrodes capable of addressing distinct populations of neural elements. The number of such channels available to any individual patient may depend on the number of implanted electrodes, the site of implantation, and patient differences such as extent and pattern of neural survival. For efficient and unambiguous information transmission it is desirable that stimulation of each channel be as independent as possible. Non-simultaneous stimulation of channels in an effort to avoid vector summation of fields and resulting channel interactions has been shown to improve scores in speech recognition tests for many patients. In some cases, manipulation of the order and/or rate of stimulation further improves speech reception, perhaps by further increasing the independence of the available channels in patients subject to non-simultaneous interactions involving transient polarization of cell membranes.

Distinct frequency bands are the sources of spectral information to be conveyed as place of stimulation via the perceptually distinct channels. The design of appropriate sets of such bands includes choices of the number of distinct bands to analyze, the overall frequency range of the set of bands, the frequency range of each individual band, and the sharpness of the band edges (filter order).

Periodicity information is conveyed by temporal variations in the stimulus amplitudes of each channel. Upper limits on the frequency of such amplitude variations arise from at least two considerations. (1) If stimuli are being presented nonsimultaneously to reduce channel interactions, then the signal on any one channel will be a series of pulses occurring at some rate of stimulation. If the amplitudes of those pulses are modulated by signals including components at frequencies greater than one half the stimulation rate, then aliasing can occur. A manifestation of an insufficient sampling rate, aliasing will add anomalous low frequency components to the amplitude modulation of the stimulus pulses. Thus the highest frequency periodicity information conveyed within any one channel should not exceed one half the pulse stimulation rate of that channel, and if the rate of stimulation is reduced (*e.g.*, to reduce nonsimultaneous channel interactions) the maximum modulation frequency may have to be reduced accordingly. [We note, however, that in certain circumstances aliasing noise may help a patient recognize the presence of high frequency speech cues.] (2) While it has been reported that some patients with implanted auditory prostheses can detect differences in periodicity information up to 2000 Hz or so (Hochmair *et al.*, 1983), most cannot discriminate such differences above a few hundred Hz (*e.g.* Shannon, 1993). Providing additional stimulus modulation components at frequencies too high for a given patient to utilize may even reduce that patient's performance levels on speech recognition tests.

Thus, when deriving a temporal envelope signal to characterize variations in energy in the chosen frequency band for each channel, it is important to use a smoothing filter to impose an appropriate upper frequency limit on such variations -- one appropriate both to the individual patient's perceptual abilities and to the particular processor's rate of stimulation on each channel.

Traditional pitch perception studies using single pure tone stimuli can be administered to patients with multichannel sound processors and multi-electrode implanted arrays. The data from such studies reflect not only the functioning of basic place and periodicity mechanisms but also artifacts resulting from processor channel design. Either some pure tones will influence the signals in more than one channel because of adjacent bandpass filter overlap, or some pure tones will fall between filters and therefore not be represented as salient electrical stimuli. The former case is typical of processors in use today. In effect, a single pure tone input to such a multichannel processor with n bands will result in one of 2n-1 distinct place information stimulation patterns, n of which correspond to stimulation on a single channel and the remaining n-1 of which correspond to stimulation of both of two adjacent channels.

While some overlap between adjacent frequency bands may enhance place pitch discrimination performance for single pure tone stimuli (Dorman, 1993), such a design raises potential problems for periodicity information and for pitch perception of real-world complex tone stimuli. The relative phase generally will be uncontrolled between the envelope variations of a single pure tone as conveyed in two channels whose bands overlap its frequency. In many cases the pure tone periodicity will be a frequency too high to be conveyed as a modulated amplitude -- either because of the aliasing constraint or because of limits in the patient's perceptual abilities.

What information will be conveyed when a complex musical tone is analyzed by such a multichannel sound processor? Consider a class of complex tones, each composed of several pure-tone partials -- one or more fundamentals and/or various upper harmonics. When such a complex tone is input to a multichannel processor that has slightly overlapping frequency bands, each partial may affect the output in a single channel exclusively or (if the partial's frequency falls in a region of band overlap) the outputs in two adjacent channels. Correspondingly, a given processor channel may convey information for (1) a single partial exclusively, (2) a single partial that also affects the output of an adjacent channel, (3) more than one partial exclusively, (4) more than one partial that also affects the output of one or both the adjacent channels, or (5) some combination of exclusive and non-exclusive partials.

In contrast to the situation for single pure tones, complex tone inputs might result in uncontrolled and/or unnatural interactions among channels, confounding perceptions of pitch or musical intervals. On the other hand, multichannel processor responses to complex tones might provide additional information useful in pitch perception. As an example of the latter possibility, note that the presence of two partials exclusively in the same channel's frequency band might well produce beating at a frequency low enough to be conveyed to (and perceived by) the patient as channel envelope modulation. Such information conceivably could provide much more support for an accurate pitch interval determination than a pair of partials each of which was conveyed in a separate channel or under less controlled circumstances (*e.g.*, in a region of overlapping frequency bands).

Approach

To explore the potential and limitations of multichannel sound processing of such complex tones, one would like as controlled a situation as possible. To this end we have constructed various tables of complex tone harmonic partials. The tables cover a range of fundamental pitches and a variety of possible configurations of processor frequency bands (in terms of number of bands, frequency ranges, and sharpness of filter edges). Various exclusivity criteria have been included (in terms of the sensitivity of the primary band and the adjacent bands to each partial's frequency).

For the purposes of the present discussion, we have included a set of tables (Tables 1 through 5) for four octaves of fundamentals extending upward from A-110 Hz in an equal-tempered chromatic scale. The channel band designs are standard 11- and 6-channel configurations routinely used for speech processors in our laboratory (Tables 1-2 and 3-5 respectively), using both 12th- and 6th-order bandpass filters (Tables 1-4 and 5 respectively) and spread over a 350-to-5500 Hz frequency range in logarithmically equal bands (*i.e.*, the bands cover equal musical intervals). Each table lists selected partials from among the lowest eight harmonics. In all these cases every listed partial lies within 1 dB of maximum sensitivity in its primary band. Listed partials additionally must meet an exclusivity requirement in terms of sufficiently reduced sensitivity in adjacent bands. Separate tables are provided for adjacent band suppression criteria of 10 (Tables 1, 3, and 5) and 20 dB (Tables 2 and 4).

Our design emphasis in the experiments constructed using such tables is to eliminate uncontrolled interaction between two bands due to partials that affect modulation envelopes in both, while preserving the possibility of two partials interacting within a band, so long as both partials affect that band's envelope exclusively. In constructing complex tones for such experiments two forms of the same tabular data are helpful. One form [part (a) of each table, labeled "Channel Assignments of Harmonic Partials"] lists the harmonic numbers of partials that meet the acceptance criteria in columns that correspond to the processor channels in which they are exclusively conveyed. In the other form [part (b) of each table, labeled "Harmonic Partials Conveyed in Single Channels"] the same information is displayed with the channel number listed in the column corresponding to each harmonic partial that meets the acceptance criteria. Comparisons of channel utilization can be accomplished most easily using the part (a) tables, while comparisons of harmonic content are best supported by the part (b) versions. In both forms the four octaves of equal-tempered fundamental frequencies are listed in order of ascending musical pitch.

Table 1(a)

Channel Assignments of Harmonic Partials
Standard RTI 12th Order Bands for 11 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 10 dB down in adjacent bands

		Channels										
Pitch	Freq	1	2	3	4	5	6	7	8	9	10	11
A	110 Hz		5	6	7,8							
B♭			4	6	7							
B		3	4	5	7	8						
C		3	4	5	6,7	8						
C♯		3	4	5	6	8						
D					6	7,8						
E♭			3	4	5	7						
E			3	4	5	6,7	8					
F			3	4	5	6	8					
F♯		2	3		5	6	7,8					
G		2			4	5,6	7					
G♯		2		3	4	5	7	8				
A	220			3	4	5	6	8				
B♭			2	3		5	6	7,8				
B			2			4	6	7				
C			2		3	4	5	7	8			
C♯			2		3	4	5	6,7	8			
D					3	4	5	6	8			
E♭				2				6	7,8			
E				2		3	4	5	7			
F				2		3	4	5	6,7	8		
F♯		1				3	4	5	6	8		
G		1			2	3		5	6	7,8		
G♯		1			2			4	5,6	7		
A	440				2		3	4	5	7	8	
B♭			1				3	4	5	6	8	
B			1			2	3		5	6	7,8	
C			1			2			4	6	7	
C♯			1			2		3	4	5	7	8
D						2		3	4	5	6,7	8
E♭				1				3	4	5	6	8
E				1			2				6	7,8
F				1			2		3	4	5	7
F♯							2		3	4	5	6,7
G					1				3	4	5	6
G♯					1			2	3			6
A	880				1			2			4	5,6
B♭								2		3	4	5
B						1				3	4	5
C						1			2	3		5
C♯						1			2			4
D						1			2		3	4
E♭									2		3	4
E							1				3	4
F							1			2		
F♯							1			2		3
G										2		3
G♯								1				3

Table 1(b)

Harmonic Partials Conveyed in Single Channels
Standard RTI 12th Order Bands for 11 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 10 dB down in adjacent bands

		Harmonics							
Pitch	Freq	1	2	3	4	5	6	7	8
A	110 Hz					2	3	4 -	4
B^{b}					2		3	4	
B				1	2	3		4	5
C				1	2	3	4 -	4	5
$C^{\#}$				1	2	3	4		5
D							4	5 -	5
E^{b}				2	3	4		5	
E				2	3	4	5 -	5	6
F				2	3	4	5		6
$F^{\#}$			1	2		4	5	6 -	6
G			1		4	5 -	5	6	
$G^{\#}$			1	3	4	5		6	7
A	220			3	4	5	6		7
B^{b}			2	3		5	6	7 -	7
B			2		5		6	7	
C			2	4	5	6		7	8
$C^{\#}$			2	4	5	6	7 -	7	8
D				4	5	6	7		8
E^{b}			3				7	8 -	8
E			3	5	6	7		8	
F			3	5	6	7	8 -	8	9
$F^{\#}$		1		5	6	7	8		9
G		1	4	5		7	8	9 -	9
$G^{\#}$		1	4		7	8 -	8	9	
A	440		4	6	7	8		9	10
B^{b}		2		6	7	8	9		10
B		2	5	6		8	9	10 -	10
C		2	5		8		9	10	
$C^{\#}$		2	5	7	8	9		10	11
D			5	7	8	9	10 -	10	11
E^{b}		3		7	8	9	10		11
E		3	6				10	11 -	11
F		3	6	8	9	10		11	
$F^{\#}$			6	8	9	10	11 -	11	
G		4		8	9	10	11		
$G^{\#}$		4	7	8			11		
A	880	4	7		10	11 -	11		
B^{b}			7	9	10	11			
B		5		9	10	11			
C		5	8	9		11			
$C^{\#}$		5	8		11				
D		5	8	10	11				
E^{b}			8	10	11				
E		6		10	11				
F		6	9						
$F^{\#}$		6	9	11					
G			9	11					
$G^{\#}$		7		11					

Table 2(a)

Channel Assignments of Harmonic Partials
Standard RTI 12th Order Bands for 11 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 20 dB down in adjacent bands

		Channels										
Pitch	Freq	1	2	3	4	5	6	7	8	9	10	11
A	110 Hz			6	8							
B^b				6	7							
B		3	4	5	7							
C		3	4	5		8						
$C^\#$		3		5	6	8						
D					6	7						
E^b				4		7						
E			3	4	5	7	8					
F			3	4	5	6	8					
$F^\#$		2				6	8					
G		2					7					
$G^\#$		2		3	4	5	7					
A	220			3	4	5	6	8				
B^b				3			6	8				
B			2				6	7				
C			2			4	5	7				
$C^\#$					3	4	5		8			
D					3		5	6	8			
E^b				2				6	7			
E				2			4		7			
F				2		3	4	5		8		
$F^\#$		1				3	4	5	6	8		
G		1							6	7		
$G^\#$		1			2					7		
A	440				2		3	4	5	7	8	
B^b							3	4	5	6	8	
B			1				3			6	8	
C			1			2					7	
$C^\#$						2			4	5	7	
D								3	4	5	6	8
E^b				1				3		5	6	8
E				1			2				6	7,8
F				1			2			4		7
$F^\#$							2		3	4	5	7
G									3		5	6
$G^\#$					1							6
A	880				1			2			4	6
B^b								2		3	4	5
B										3	4	5
C						1						5
$C^\#$						1			2			
D									2		3	4
E^b											3	4
E							1				3	4
F							1			2		
$F^\#$							1			2		
G												3
$G^\#$												3

Table 2(b)

Harmonic Partials Conveyed in Single Channels
Standard RTI 12th Order Bands for 11 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 20 dB down in adjacent bands

		Harmonics							
Pitch	Freq	1	2	3	4	5	6	7	8
A	110 Hz						3		4
B♭							3	4	
B				1	2	3		4	
C				1	2	3			5
C♯				1		3	4		5
D							4	5	
E♭					3			5	
E				2	3	4		5	6
F				2	3	4	5		6
F♯			1				5		6
G			1					6	
G♯			1	3	4	5		6	
A	220			3	4	5	6		7
B♭				3			6		7
B			2				6	7	
C			2		5	6		7	
C♯				4	5	6			8
D				4		6	7		8
E♭			3				7	8	
E			3		6			8	
F			3	5	6	7			9
F♯		1		5	6	7	8		9
G		1					8	9	
G♯		1	4					9	
A	440		4	6	7	8		9	10
B♭				6	7	8	9		10
B		2		6			9		10
C		2	5					10	
C♯			5		8	9		10	
D				7	8	9	10		11
Eb		3		7		9	10		11
E		3	6				10	11	11
F		3	6		9			11	
F♯			6	8	9	10		11	
G				8		10	11		
G♯		4					11		
A	880	4	7		10		11		
B♭			7	9	10	11			
B				9	10	11			
C		5				11			
C♯		5	8						
D			8	10	11				
E♭				10	11				
E		6		10	11				
F		6	9						
F♯		6	9						
G				11					
G♯				11					

Table 3(a)

Channel Assignments of Harmonic Partials
Standard RTI 12th Order Bands for 6 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 10 dB down in adjacent bands

				Channels			
Pitch	Freq	1	2	3	4	5	6
A	110 Hz	4	6,7				
$B^\flat$		4	5,6,7	8			
B		3,4	5,6	8			
C		3,4	5,6	7,8			
$C^\sharp$		3	5,6	7,8			
D		3	4,5	7,8			
$E^\flat$		3	4,5	6,7,8			
E		3	4,5	6,7,8			
F		3	4	6,7			
$F^\sharp$		2	4	5,6,7	8		
G		2	3,4	5,6	8		
$G^\sharp$		2	3,4	5,6	7,8		
A	220	2	3	5,6	7,8		
$B^\flat$		2	3	4,5	7,8		
B		2	3	4,5	6,7,8		
C		2	3	4,5	6,7		
$C^\sharp$			3	4	6,7		
D			2	4	5,6,7	8	
$E^\flat$			2	3,4	5,6	8	
E			2	3,4	5,6	7,8	
F			2	3	5	7,8	
$F^\sharp$		1	2	3	4,5	7,8	
G		1	2	3	4,5	6,7,8	
$G^\sharp$		1	2	3	4,5	6,7	
A	440	1		3	4	6,7	
$B^\flat$		1		2	4	5,6,7	8
B		1		2	3,4	5,6	8
C		1		2	3	5,6	7,8
$C^\sharp$				2	3	5	7,8
D			1	2	3	4,5	7,8
$E^\flat$			1	2	3	4,5	6,7,8
E			1	2	3	4	6,7,8
F			1			4	6,7
$F^\sharp$			1		2	4	5,6,7
G			1		2	3,4	5,6
$G^\sharp$			1		2	3	5,6
A	880				2	3	5,6
$B^\flat$				1	2	3	4,5
B				1	2	3	4,5
C				1		3	4,5
$C^\sharp$				1			4
D				1		2	4
$E^\flat$				1		2	3,4
E				1		2	3,4
F						2	3
$F^\sharp$					1	2	3
G					1	2	3
$G^\sharp$					1		3

Table 3(b)

Harmonic Partials Conveyed in Single Channels
Standard RTI 12th Order Bands for 6 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 10 dB down in adjacent bands

						Harmonics								
Pitch	Freq	1	2	3		4		5		6		7		8
A	110 Hz					1				2	-	2		
B♭						1		2	-	2	-	2		3
B				1		1		2	-	2				3
C				1		1		2	-	2		3	-	3
C♯				1				2	-	2		3	-	3
D				1		2	-	2				3	-	3
E♭				1		2	-	2		3	-	3	-	3
E				1		2	-	2		3	-	3	-	3
F				1		2				3	-	3		
F♯			1			2		3	-	3	-	3		4
G			1	2	-	2		3	-	3				4
G♯			1	2	-	2		3	-	3		4	-	4
A	220		1	2				3	-	3		4	-	4
B♭			1	2		3	-	3				4	-	4
B			1	2		3	-	3		4	-	4	-	4
C			1	2		3	-	3		4	-	4		
C♯				2		3				4	-	4		
D			2			3		4	-	4	-	4		5
E♭			2	3	-	3		4	-	4				5
E			2	3	-	3		4	-	4		5	-	5
F			2	3				4				5	-	5
F♯		1	2	3		4	-	4				5	-	5
G		1	2	3		4	-	4		5	-	5	-	5
G♯		1	2	3		4	-	4		5	-	5		
A	440	1		3		4				5	-	5		
B♭		1	3			4		5	-	5	-	5		6
B		1	3	4	-	4		5	-	5				6
C		1	3	4				5	-	5		6	-	6
C♯			3	4				5				6	-	6
D		2	3	4		5	-	5				6	-	6
E♭		2	3	4		5	-	5		6	-	6	-	6
E		2	3	4		5				6	-	6	-	6
F		2				5				6	-	6		
F♯		2	4			5		6	-	6	-	6		
G		2	4	5	-	5		6	-	6				
G♯		2	4	5				6	-	6				
A	880		4	5				6	-	6				
B♭		3	4	5		6	-	6						
B		3	4	5		6	-	6						
C		3		5		6	-	6						
C♯		3				6								
D		3	5			6								
E♭		3	5	6	-	6								
E		3	5	6	-	6								
F			5	6										
F♯		4	5	6										
G		4	5	6										
G♯		4		6										

Table 4(a)

Channel Assignments of Harmonic Partials
Standard RTI 12th Order Bands for 6 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 20 dB down in adjacent bands

		Channels					
Pitch	Freq	1	2	3	4	5	6
A	110 Hz	4	6,7				
B^b		4	6				
B		3,4	5,6	8			
C		3	5,6	8			
C$^\#$		3	5	7,8			
D		3	5	7,8			
E^b		3	4,5	7,8			
E		3	4	6,7			
F			4	6,7			
F$^\#$		2	4	6			
G		2	4	5,6	8		
G$^\#$		2	3	5	8		
A	220	2	3	5	7,8		
B^b		2	3	5	7,8		
B		2	3	4,5	7		
C			3	4	6,7		
C$^\#$				4	6,7		
D				4	6		
E^b			2	4	5,6	8	
E			2	3	5	8	
F			2	3	5	7,8	
F$^\#$		1	2	3	5	7,8	
G		1	2	3	4	7	
G$^\#$		1			4	6,7	
A	440	1			4	6	
B^b		1			4	6	
B		1		2		5,6	8
C				2	3	5	8
C$^\#$				2	3	5	7,8
D				2	3	5	7,8
E^b			1	2	3	4	7,8
E			1			4	6,7,8
F			1			4	6,7
F$^\#$			1			4	6,7
G			1		2		5,6
G$^\#$					2	3	5,6
A	880				2	3	5,6
B^b					2	3	5
B				1		3	4,5
C				1			4,5
C$^\#$				1			4
D				1			4
E^b				1		2	4
E						2	3,4
F						2	3
F$^\#$						2	3
G					1		3
G$^\#$					1		3

Table 4(b)

Harmonic Partials Conveyed in Single Channels
Standard RTI 12th Order Bands for 6 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 20 dB down in adjacent bands

		Harmonics							
Pitch	Freq	1	2	3	4	5	6	7	8
A	110 Hz				1		2 -	2	
B^{b}					1		2		
B				1 -	1	2 -	2		3
C				1		2 -	2		3
$C^{\#}$				1		2		3 -	3
D				1		2		3 -	3
E^{b}				1	2 -	2		3 -	3
E				1	2		3 -	3	
F					2		3 -	3	
$F^{\#}$			1		2		3		
G			1		2	3 -	3		4
$G^{\#}$			1	2		3			4
A	220		1	2		3		4 -	4
B^{b}			1	2		3		4 -	4
B			1	2	3 -	3		4	
C				2	3		4 -	4	
$C^{\#}$					3		4 -	4	
D					3		4		
E^{b}			2		3	4 -	4		5
E			2	3		4			5
F			2	3		4		5 -	5
$F^{\#}$		1	2	3		4		5 -	5
G		1	2	3	4			5	
$G^{\#}$		1			4		5 -	5	
A	440	1			4		5		
B^{b}		1			4		5		
B		1	3			5 -	5		6
C			3	4		5			6
$C^{\#}$			3	4		5		6 -	6
D			3	4		5		6 -	6
E^{b}		2	3	4	5			6 -	6
E		2			5		6 -	6 -	6
F		2			5		6 -	6	
$F^{\#}$		2			5		6 -	6	
G		2	4			6 -	6		
$G^{\#}$			4	5		6 -	6		
A	880		4	5		6 -	6		
B^{b}			4	5		6			
B		3		5	6 -	6			
C		3			6 -	6			
$C^{\#}$		3			6				
D		3			6				
E^{b}		3	5		6				
E			5	6 -	6				
F			5	6					
$F^{\#}$			5	6					
G		4		6					
$G^{\#}$		4		6					

Table 5(a)

Channel Assignments of Harmonic Partials
Standard RTI 6th Order Bands for 6 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 10 dB down in adjacent bands

		Channels					
Pitch	Freq	1	2	3	4	5	6
A	110 Hz	4	6,7				
B^b		4	6				
B		3,4	5,6	8			
C		3	5,6	8			
$C^\#$		3	5	7,8			
D		3	5	7,8			
E^b		3	4,5	7			
E		3	4	6,7			
F			4	6			
$F^\#$			4	6			
G		2	4	5,6			
$G^\#$		2	3	5	8		
A	220	2	3	5	8		
B^b		2	3	5	7,8		
B		2	3	4	7,8		
C			3	4	7		
$C^\#$				4	6,7		
D				4	6		
E^b			2		6	8	
E			2	3	5,6	8	
F			2	3	5	7,8	
$F^\#$			2	3	5	7,8	
G		1	2	3	5	7	
$G^\#$		1			4	6,7	
A	440	1			4	6,7	
B^b		1			4	6	
B		1		2	4	5,6	8
C				2		5	8
$C^\#$				2	3	5	7,8
D				2	3	5	7,8
E^b			1		3	4	7,8
E			1		3	4	6,7
F			1			4	6,7
$F^\#$			1			4	6,7
G			1				5,6
$G^\#$					2	3	5,6
A	880				2	3	5,6
B^b					2	3	5
B				1	2	3	4,5
C				1			4,5
$C^\#$				1			4
D				1			4
E^b						2	4
E						2	3,4
F						2	3
$F^\#$						2	3
G							3
$G^\#$					1		3

Table 5(b)

Harmonic Partials Conveyed in Single Channels
Standard RTI 6th Order Bands for 6 Channel Processors
Within 1 dB of peak sensitivity in indicated band
and at least 10 dB down in adjacent bands

						Harmonics								
Pitch	Freq	1	2	3		4		5		6		7		8
A	110 Hz					1				2	-	2		
B^{b}						1				2				
B				1	-	1		2	-	2				3
C				1				2	-	2				3
$C^{\#}$				1				2				3	-	3
D				1				2				3	-	3
E^{b}				1		2	-	2				3		
E				1		2				3	-	3		
F						2				3				
$F^{\#}$						2				3				
G			1			2		3	-	3				
$G^{\#}$			1	2				3						4
A	220		1	2				3						4
B^{b}			1	2				3				4	-	4
B			1	2		3						4	-	4
C				2		3						4		
$C^{\#}$						3				4	-	4		
D						3				4				
E^{b}			2							4				5
E			2	3				4	-	4				5
F			2	3				4				5	-	5
$F^{\#}$			2	3				4				5	-	5
G		1	2	3				4				5		
$G^{\#}$		1				4				5	-	5		
A	440	1				4				5	-	5		
B^{b}		1				4				5				
B		1	3			4		5	-	5				6
C			3					5						6
$C^{\#}$			3	4				5				6	-	6
D			3	4				5				6	-	6
E^{b}		2		4		5						6	-	6
E		2		4		5				6	-	6		
F		2				5				6	-	6		
$F^{\#}$		2				5				6	-	6		
G		2						6	-	6				
$G^{\#}$			4	5				6	-	6				
A	880		4	5				6	-	6				
B^{b}			4	5				6						
B		3	4	5		6	-	6						
C		3				6	-	6						
$C^{\#}$		3				6								
D		3				6								
E^{b}			5			6								
E			5	6	-	6								
F			5	6										
$F^{\#}$			5	6										
G				6										
$G^{\#}$		4		6										

A glance at Tables 1 through 5 reveals distinct patterns in channel utilization and harmonic availability as the fundamental frequency moves along a chromatic musical scale. (The number of harmonic partials meeting each set of selection criteria also is shown explicitly in Table 7.) The contrasts from step to step along the scale are heightened by either going from a 10 dB to a 20 dB exclusivity criterion (compare Tables 1 and 2 or Tables 3 and 4), or by going from 6 channels to 11 (compare Tables 3 and 1 or Tables 4 and 2). For eleven 12th-order bands and a 10 dB criterion (Table 1), the step-by-step changes in channel utilization appear much more dramatic than the concomitant differences in the harmonics conveyed (compare Tables 1a and 1b). With a 20 dB criterion, the same processor exhibits large variations of both types as the fundamental frequency is varied step by step (Tables 2a and 2b).

Table 6 displays, for each condition treated in Tables 1-5 and each channel, the high and low limits of the frequency band meeting all the applicable criteria. Also indicated are overall coverage fractions for each condition, *i.e.* the sum of the ranges of log(*f*) meeting the applicable criteria for each of the bands divided by the overall range of log(*f*) for the whole processor, expressed in percent. Note also in Table 6 that the combination of six 6th-order bands and a 20 dB criterion completely disqualifies the interior channels due to overlaps between adjacent bands.

We have chosen initially to study the same frequency band sets used for extensive earlier tests of processor performance in speech perception tasks. We note, however, that it is possible to optimize the band coverage under our present criteria by having the -1 dB points in each band occur at the same frequencies as, say, -10 dB points of the adjacent bands. Such a set of bands would result in 85.8% of the overall processor frequency range satisfying the criteria for an eleven channel, 12th-order design. The coverage would be 86.4% for an equivalent six channel, 12-th order processor.

We plan to use various combinations of the stimuli assembled in these tables to study the mechanisms of complex tone pitch perception with existing speech processors designed for implanted auditory prostheses. We anticipate that this may lead to better ways of supporting complex tone pitch perception in future processor designs -- both for better voice pitch perception within speech and for improved access to music via implanted prostheses. While the nature of electrical stimulation in such prostheses allows only the most crude mimicking of the functions of normal hearing, it also provides the possibility of stimulus patterns unattainable in normal listeners. The study of perceptions arising from such "unnatural" stimuli may provide additional insights regarding CNS processing of auditory input. Finally, we anticipate that use of such carefully constructed complex tone stimuli may constitute a useful tool in the diagnosis of significant differences among implanted patients and optimization of processors for individual patients.

Pilot Study Subject

We have conducted a pilot study using these materials with a single patient (SR2) chosen on the basis of (1) excellent performance with existing processor designs, (2) exceptional

Table 6

Frequency Ranges Conveyed to Single Channels
Within 1 dB of peak sensitivity in indicated band

Channel	10 dB down in adjacent bands Frequency Range (Hz)			20 dB down in adjacent bands Frequency Range (Hz)		
	Standard RTI 12th Order Bands for 11 Channel Processors					
1	355	437		355	424	
2	460	563		475	545	
3	592	724		612	700	
4	761	929		786	898	
5	977	1194		1009	1154	
6	1254	1533		1296	1482	
7	1612	1968		1664	1903	
8	2070	2527		2136	2439	
9	2658	3240		2742	3130	
10	3411	4150		3513	3980	
11	4370	5440		4500	5440	
			81.5%			57.4%
	Standard RTI 12th Order Bands for 6 Channel Processors					
1	359	529		359	499	
2	580	836		615	787	
3	915	1324		969	1245	
4	1450	2089		1536	1958	
5	2291	3279		2419	3037	
6	3613	5412		3792	5412	
			83.0%			60.9%
	Standard RTI 6th Order Bands for 6 Channel Processors					
1	370	500		370	430	
2	610	800				
3	960	1200				
4	1600	1980				
5	2425	3100				
6	3800	5300		4300	5300	
			59.6%			

Table 7

Number of Partials Meeting Selection Criteria
for Each Fundamental and in Each Condition

Pitch	Criteria					
	Channels:	11	11	6	6	6
	Band Filter Order:	12	12	12	12	6
	Adjacent Channels (dB)	-10	-20	-10	-20	-10
A	110 Hz	4	2	3	3	3
B♭		3	2	5	2	2
B		5	4	5	5	5
C		6	4	6	4	4
C♯		5	4	5	4	4
D		3	2	5	4	4
E♭		4	2	6	5	4
E		6	5	6	4	4
F		5	5	4	3	2
F♯		6	3	6	3	2
G		5	2	6	5	4
G♯		6	5	7	4	4
A	220	5	5	6	5	4
B♭		6	3	6	5	5
B		4	3	7	5	5
C		6	4	6	4	3
C♯		7	4	4	3	3
D		5	4	6	2	2
E♭		4	3	6	5	3
E		5	3	7	4	5
F		7	5	5	5	5
F♯		6	6	7	6	5
G		7	3	8	5	5
G♯		6	3	7	4	4
A	440	6	6	5	3	4
B♭		6	5	7	3	3
B		7	4	7	5	6
C		5	3	7	4	3
C♯		7	4	5	5	5
D		7	5	7	5	5
E♭		6	5	8	6	5
E		5	5	7	5	5
F		6	4	4	4	4
F♯		6	5	6	4	4
G		5	3	6	4	3
G♯		4	2	5	4	4
A	880	5	4	4	4	4
B♭		6	4	5	3	3
B		4	3	5	4	5
C		4	2	4	3	3
C♯		3	2	2	2	2
D		4	3	3	2	2
E♭		3	2	4	3	2
E		3	3	4	3	3
F		2	2	2	2	2
F♯		3	2	3	2	2
G		2	1	3	2	1
G♯		2	1	2	2	2

analytic and descriptive abilities regarding his auditory percepts, (3) experience as a musician--both before losing his normal hearing and recently with a clinical prosthesis, and (4) familiarity with some basic music theory. Since both statistical data and anecdotal comparisons were of interest at this initial stage, our pilot study was constructed around a set of complex tone stimulus pairs appropriate for both approaches.

Pilot Study Stimuli

The specific complex tone pairs were chosen to probe a variety of potentially interesting perceptual effects, some of which will be discussed later in this preliminary report. 118 pairs were constructed for use with a standard 6-channel continuous interleaved sampling (CIS) processor [MP163b], and another 55 pairs for similar use with an 11-channel virtual channel interleaved sampling (VCIS) design [MP200b]. Each stimulus tone was approximately 0.5 seconds in duration (22,000 samples at 44.1 kHz), including approximately 11 msec each of linear fade-in and fade-out (500 samples each). Each stimulus was presented from a digitally-synthesized file of 16-bit samples.

Each of the complex tones used in such sequential comparisons could be presented at a perceptually equalized loudness. The overall amplitude factors for each such complex tone necessary to achieve a common perceived loudness could be determined in advance and in a neutral context, *viz.* through comparisons with a single standard sound not among the tones used in the subsequent tests themselves. For our pilot studies, however, we chose to use a fixed relative gain among test tokens, so that saliency comparisons among constituent partials yield direct information. Selected loudness balanced studies may well follow. Happily, with a master gain control set to obtain most comfortable loudness for a full 8-harmonic complex G-392 Hz or E^b-622 Hz, subject SR2 heard all of the other stimulus tones clearly and comfortably.

Following the spectral envelopes of typical musical tones, relative nth harmonic amplitudes of $1/n$ and $1/n^2$ were chosen for the first comparisons among our complex tones. $1/n$ was used in our pilot studies in order to ensure relatively strong beat phenomena. The 6 dB/octave preemphasis filter typically included in speech processors for implanted auditory prostheses effectively contributes an additional weighting proportional to n over *part* of the represented spectrum. (As noted below, a check for the significance of this effect was included in the pilot studies.) In selected cases where the presence of particular partials produced marked effects in complex tone pitch percepts the same partial might also need to be evaluated with its relative phase shifted by π.

Pilot Study Methods

The statistical portion of our pilot study was administered by an interactive computer program. A pair of complex tone stimuli was presented to the subject's processor, after which the subject could use a mouse to select any of six responses, or to request that presentation of the pair be repeated. Figure 1 indicates the general form of the subject's response screen. The responses corresponded to (1) the second tone having an unambiguously ***higher*** pitch than the first, (2) the second tone having a ***lower*** pitch, (3) the two tones having the ***same*** pitch, (4) the second tone seeming to be ***both*** higher and lower in pitch than the first, (5) "***can't say***", and (6) "***inaudible***". Subject SR2 never availed himself of the fifth or sixth response. The 118 six-channel pairs and the 55 eleven-channel pairs were assigned serial numbers, by which they were block randomized. The order of presentation of the two stimuli within each pair was reversed from block to block, with even-numbered pairs presented in "normal" order for one block and in reversed order for the next, and *vice versa* for the odd-numbered pairs. Normal order within a pair was defined as ***ascending*** fundamental for sequential intervals and ***narrowing*** interval for sequences of simultaneous multi-fundamental intervals. A minimum of four blocks were presented at one time for each condition. The number of presentations requested by the subject was recorded for each pair, along with his eventual response and the order of presentation.

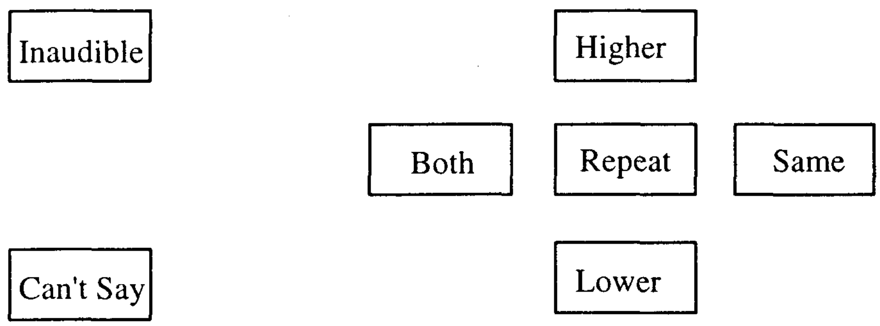


Figure 1. Subject's Response Screen

The distinct conditions under which such tests were given included presentation of the two tones of each pair both with essentially no delay between them and with a one-second delay. In addition to the standard six and eleven channel configurations, both delay and no-delay tests were conducted with a special variation of the six channel processor, one with a compensating digital filter to cancel the amplitude effect of the 6 dB/octave preemphasis commonly used in speech processors. The total number of presentations of each pair in each condition was:

processor:	no delay:	1-sec delay:
standard 6 channels	8	12
6 channels, no preemphasis	4	4
standard 11 channels	8	12

In each case, one half of the presentations were in reversed order. All the processors used in this pilot study had 400 Hz , first-order low-pass filtering of the amplitude envelope for each channel. The stimulation rate was 1364 pps for each channel of the 11-channel processor and 2525 pps for each channel of the 6-channel processors.

Our initial statistical survey was completed before the anecdotal portions of our pilot study were begun, to avoid biasing the statistical results by any strategies or analytic categories acquired by the subject in the course of describing his percepts. The same complex tone stimulus pairs were used in the anecdotal comparisons, presented manually by an experimenter and occasionally augmented by additional comparison tones. The anecdotal portions of the study were divided by category and experimental condition into approximately 30 segments, each of which began with a highly structured series of comparisons and questions, followed by limited further investigation of any particularly intriguing findings.

In the remainder of this preliminary report we shall discuss examples of the types of issues that can be addressed using these complex tone stimuli -- the kinds of considerations that influenced the design of specific tone pairs used in our pilot study. Some of the selected examples will be accompanied by statistical and/or anecdotal data from the pilot study. Those data will be shown to suggest several different directions for further investigation, including: (1) the reintroduction of some harmonics that *don't* meet our exclusivity criteria to assess their effect on the salience of pitch differences that were reliably detected in the pilot studies, (2) studies of pitch interval comparisons and identification (both for sequential and simultaneous presentation), (3) studies of consonance/dissonance perception and of timbre judgments, (4) studies of subjects' abilities to match the pitch of their own voices to a presented tone (both when monitoring their own voices via the same processor and when unmonitored), (5) focusing on the rare but striking and repeatable exceptions to some of the most consistent patterns within the pilot data, (6) "constituent studies" in which subjects are asked whether certain relatively simple complex tones are contained within a more complex stimulus, (7) additional trials in cases for which the pilot study data establish statistical significance for a pattern but are insufficient to determine correlations with respect to stimulus parameters, and (8) studies of learning effects such as the discovery of perceptual ambiguity after repeated comparisons or the sudden appearance of a new percept that then dominates subsequent judgments.

For purposes of discussion it is useful to consider separately complex tones composed of harmonics of a single common fundamental (whether or not the fundamental itself is present) and complex tones that combine harmonic partials of two distinct fundamentals (*i.e.*, a complex tone interval). Slightly different ways of characterizing the parameters of each complex tone pair will be used in those two cases.

Figure 2 indicates the layout of a display we have devised to convey substantial amounts of information about a pair of complex tone stimuli in a form that is basically tabular but with elements arranged to make certain patterns easy to recognize. The left half of each such display will describe one tone of a comparison pair and the right half the other. Within each half separate columns will display the harmonic number of each component or partial, the harmonic frequency f_h of each, the number of the processor channel in which each is (exclusively) conveyed, and the frequencies f_b of any intrachannel beats. Each fundamental will be indicated both in musical notation and in frequency, although the fundamental itself may well not be present in the stimulus. Differences between complex tone pairs will be characterized in terms of four parameters: the average frequency f_{av} of the harmonics present, the average channel number c_{av}, a harmonically-weighted average channel number c_{hw} (each channel weighted by its relative amplitude, e.g. 1/n for the nth harmonic), and any intrachannel beat frequencies f_b. Between the values for these parameters will be flags indicating at a glance whether each increases (/), remains the same (-), or decreases (\) across the complex tone pair, and whether any beat disappears (x) or appears (*).

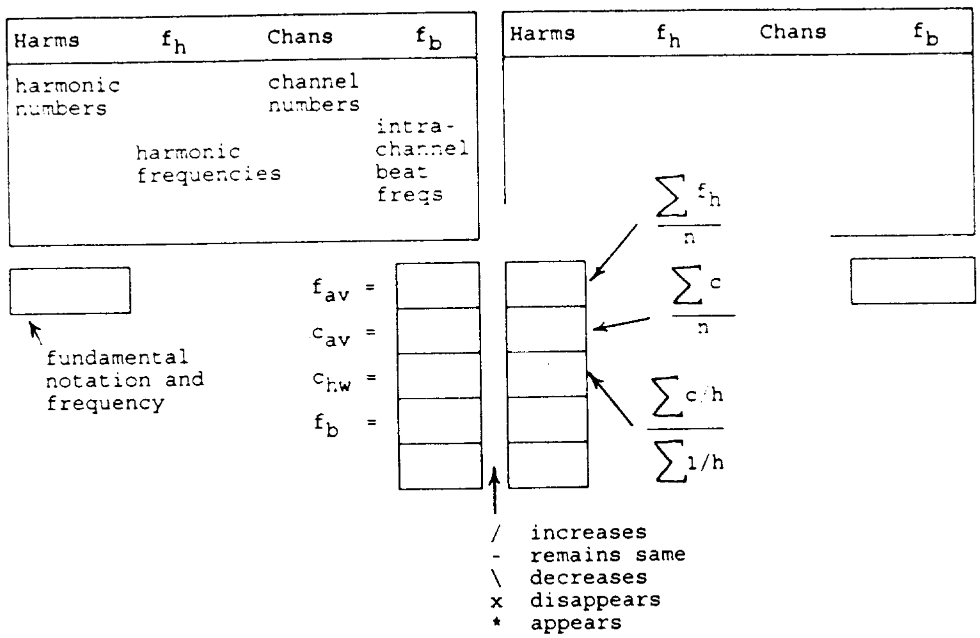


Figure 2. Key to Stimulus Structure Displays

The layout in Figure 2 is the one used when each complex tone of a pair is composed of harmonics of a single fundamental. For complex tones that combine harmonic partials of two distinct fundamentals, there will be a few differences. The first column ("Harms") will become two columns, labeled "Ha" and "Hb", one for the harmonics of each fundamental. The box containing "fundamental notation and frequency" in Figure 2 will convey that information about the lower fundamental, while a second box will include the upper fundamental's musical notation and the frequency ratio between the two fundamentals expressed as a ratio. Finally, the average frequency parameter will be the average of all *distinct* frequencies. Thus degeneracies involving different harmonics of the two fundamentals will be tabulated separately, but will not receive double weight in f_{av}.

Another type of display, to be used to convey survey statistical results throughout the remainder of this report, is shown in Figure 3. Each box in this display contains a bar graph with four bars, corresponding to the second (in normal order) of a pair of complex tones being perceived as Higher in pitch, the Same pitch, Lower in pitch or Both higher and lower in pitch with respect to the first. In this key all the bars are shown, illogically, at full scale. Full scale in each case corresponds to 100% of the responses represented in the box. The uppermost box in each such display summarizes the aggregate results for the subset of complex tone pairs represented. Results obtained for processors with and without normal preemphasis are shown separately in the two lower boxes in the same (center) column, with each of those categories being further subdivided in the boxes to either side according to whether or not a one-second delay was presented between the tones of each pair. In the outermost columns those results are in turn subdivided by order of presentation, i.e. normal or reverse. This last comparison is made within single boxes, with dual half-height scales again summing to 100%. Thus successive summations occur as one moves horizontally toward the center column and then to the top of that column, and many comparisons of likely interest are available side-by-side without intervening material.

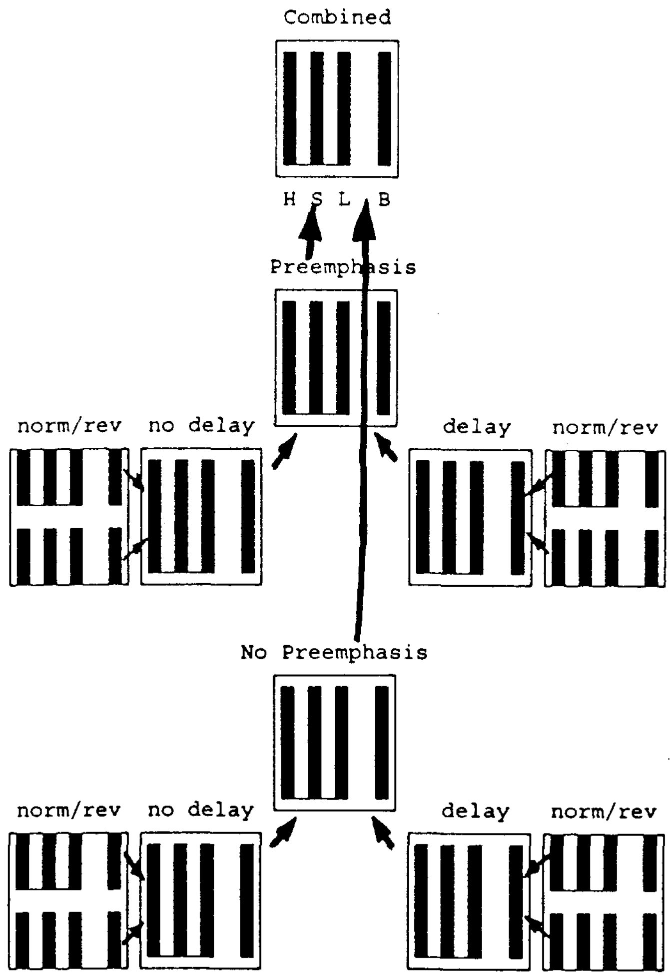


Figure 3. Key to Statistical Results Displays

Each such display will be accompanied by an indication of how many different stimulus pairs are being summarized and the total number n of combined presentations. For six channel processor data, then, the number of presentations contributing from various parts of this display will be:

n

(5/7)n

(2/7)n (3/7)n

(2/7)n

n/7 n/7

Harmonic Partials of a Single Fundamental

Pitch salience of a single complex tone: Among our available 6-channel, 12th-order, 10 dB complex tones (Table 3), we find two fundamentals with a full set of 8 harmonics meeting the criteria: G-392 Hz and E^{b}-622 Hz. Among the lower pitch conditions we select two additional tones: G-196 Hz and $G^{\#}$-208 Hz, with 7 and 6 partials meeting the criteria respectively. The allocations of partials to the six channels is as follows for these four complex tones:

Tone	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6
G-392	1	2	3	4,5	6,7,8	
E^{b}-622		1	2	3	4,5	6,7,8
G-196	2	3,4	5,6	7,8		
$G^{\#}$-208	2	3,4	5,6	8		

Several potentially useful types of pitch cues are represented within and among these four tones. Comparisons of patient percepts via such a 6-channel, 12th-order processor for input tones utilizing various subsets of these partials should provide some indication as to which, if any, of these cues are in fact salient for electrical stimulation. The G-392 and E^{b}-622 pair offer identical patterns of channel assignment but in different channels, with a substantial fundamental pitch difference. Within each of those tones are a variety of possible combinations of place and periodicity cues. Subsets of their harmonics can be used to support studies of the dependence of percepts on absolute channel assignment, for instance. The G-196 and G#-208 pair, on the other hand, provides two tones whose fundamental frequencies are separated by one semitone, with six common harmonics conveyed unambiguously in identical channels.

Before proceeding to examples of specific perceptual comparison experiments it may be helpful to demonstrate the dramatically different multichannel stimulation patterns that result from interchannel and intrachannel beats between adjacent harmonics in complex tones. Consider three pairs of adjacent harmonics (3 and 4, 4 and 5, 5 and 6) of a G-196 fundamental. In Figure 4 are plotted the first 100 ms or so of the envelope amplitudes of channels one through four recorded from a six channel CIS processor as it processed each of those three harmonic pairs. Such envelopes are the signals that, appropriately mapped onto a patient's dynamic ranges, modulate the nonsimultaneous pulses delivered to each channel. In the first case, harmonics 3 and 4 both affect only the second channel's envelope. The component harmonics are at 588 and 784 Hz and a strong beat is seen at their difference frequency -- the 196 Hz fundamental. In the second case harmonic 4 causes an envelope in channel 2 and harmonic 5 one in channel 3, and the effect of each is at least 10 dB less in adjacent channels. In the final case harmonics 5 and 6 both affect channel 3's envelope and cause another strong 196 Hz beat. This time the stimulus component frequencies are at 980 and 1176 Hz, well above most patients' rate discrimination capabilities.

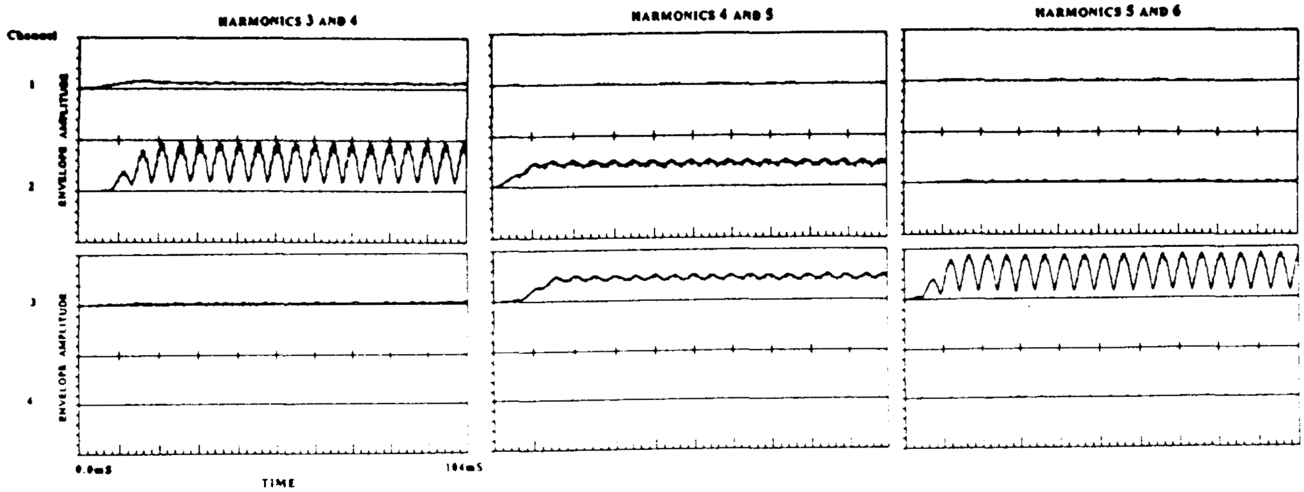


Figure 4. Channel Envelopes for Three Pairs of Adjacent Harmonics

Perception of an absent fundamental: A classic fundamental tracking (implied fundamental) demonstration provides a vehicle for several interesting comparisons. If a tone composed of harmonics 4, 5, 6, and 8 is presented in an appropriate context to a subject with normal hearing, the perceived pitch of that complex tone will correspond to the (absent) fundamental (harmonic 1). Removal of harmonic 5 will cause the perceived fundamental to jump up by an octave as harmonics 4, 6, and 8 are interpreted as the second, third, and fourth harmonics of a higher (again absent) fundamental. When harmonic 6 is removed as well, harmonic 8 will be interpreted as the second harmonic of the other remaining partial, and the perceived fundamental will ascend by an additional octave.

Both G-196 and G#-208 present harmonic 4 in channel 2, harmonics 5 and 6 in channel 3, and harmonic 8 in channel 4. Removing harmonic 5 eliminates the only beating within a channel but continues stimulation on all three channels, while removing harmonic 6 then eliminates a channel. Figure 5 shows this structure for the G-196 fundamental.

Harms	f_h	Chans	f_b
4	783	2	
5	979	3	
		3	196
6	1175	3	
8	1567	4	

Harms	f_h	Chans	f_b
4	783	2	
6	1175	3	
8	1567	4	

G	196

f_{av} =	1126	/	1175
c_{av} =	3.0	-	3.0
c_{hw} =	2.8	-	2.8
f_b =	196	x	

G	196

104-68

10468

Figure 5. Fundamental Tracking Comparison, Low Frequency

G-392 and E^b-622 offer a different pattern, as shown in Figure 6, with harmonics 4 and 5 presented to one channel and harmonics 6 and 8 to a different channel. When all four partials are present, the beat rate in the lower channel will be at the frequency of harmonic 1 while the beat rate in the higher channel will be at that of harmonic 2. Removing harmonic 5 will remove the beat from the lower channel but continue stimulation to both channels. Removing harmonic 6 then will eliminate all beating within channels but continue stimulation in both. Note that in none of these cases does the maximum or minimum frequency partial change, nor does the range of place pitch being conveyed. The average frequency of the spectrum being represented rises slightly, while the average channel number is unchanged (see Figure 2 for key to parameters).

Harms	f_h	Chans	f_b
4	1567	4	
		4	392
5	1959	4	
6	2351	5	
		5	784
8	3135	5	

G	392

224-68

Harms	f_h	Chans	f_b
4	1567	4	
6	2351	5	
		5	784
8	3135	5	

G	392

22468

f_{av} =	2253	/	2351
c_{av} =	4.5	-	4.7
c_{hw} =	4.4	-	4.5
f_b =	392	x	
	784	-	784

Figure 6. Fundamental Tracking Comparison, High Frequency

Note also that the beat rates within single channels included in these two sets of comparisons include 196, 392, and 784 Hz, allowing evaluation of the effects of various smoothing filter cutoff frequency choices and the extent of a patient's ability to make use of high frequency periodicity information.

Based on the context sensitivity of the implied fundamental perceptions of subjects with normal hearing, one might expect results for this part of our pilot survey to be highly dependent on order of presentation of the complex tone pairs and on whether or not there was a delay between the two tones of a pair. Figure 7 displays combined survey results for the lower two fundamentals (196 and 208 Hz, including the stimulus pair of Figure 5). Subject SR2 heard the 4-6-8 combination of harmonics as being higher in pitch than the 4-5-6-8 combination . This result did not appear to depend on delay, order of presentation, or preemphasis.

Figure 8 shows results for the 392-Hz fundamental in the same conditions (the stimulus pair of Figure 6). Here there are examples of substantial differences in responses depending on delay, preemphasis, and order of presentation. Such differences also were observed in the 4-6-8 combination comparisons with 4-8 for all four fundamentals. There is ample consistency and structure in these pilot survey data, despite large uncontrolled variations in presentation context, to warrant more extensive and detailed studies.

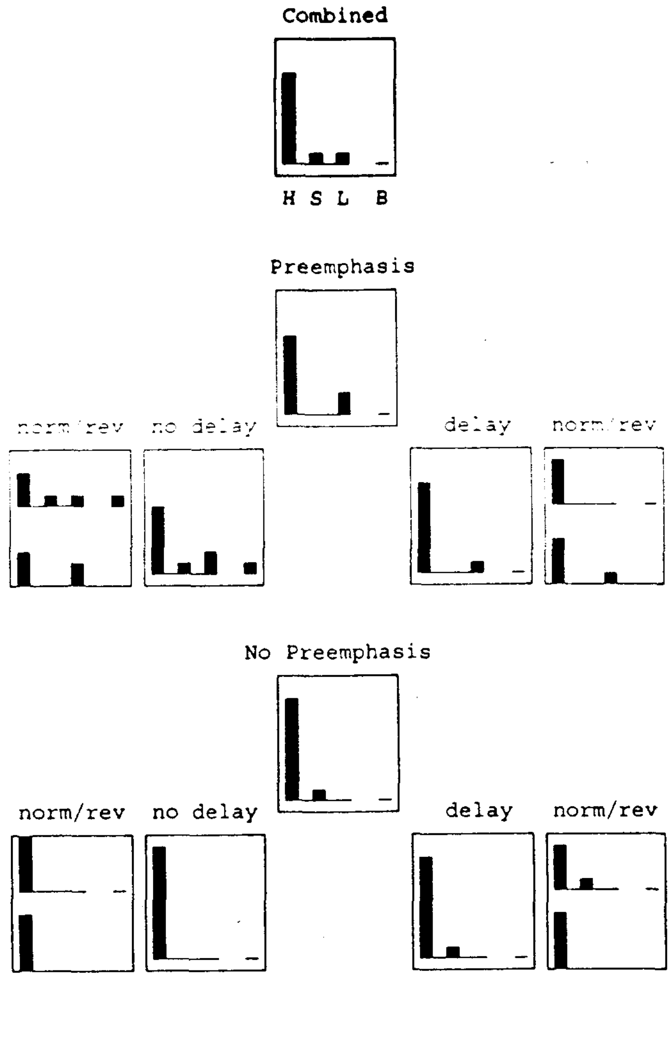


Figure 7. Fundamental Tracking Comparison, Low Frequency
2 Stimulus pairs, n = 56

The presentation context was carefully controlled in the anecdotal studies with these stimuli with, for instance, several presentations of a 4-5-6-8 combination followed by only a single presentation of the corresponding 4-6-8 for comparison. Subject SR2 described the 4-6-8 combination as definitely higher in pitch than 4-5-6-8 for the three lowest fundamentals, and as identical in pitch for the 622 Hz fundamental. He volunteered that in the 196 Hz case the difference "might be an octave", but judged the intervals as less than an octave in the other cases. The 4-6-8 to 4-8 transitions were described as identical in pitch except for the 196 Hz case. In that case the 4-8 condition was described as being definitely lower in pitch, in agreement with the survey results. SR2 then proceeded to volunteer that "[the 4-8 combination] was a bit thinner and more hollow than [the 4-6-8 combination]" and that the two were "related, probably by an octave relationship".

In a related survey study, with the two higher fundamentals, we had SR2 compare 4-5 combinations of harmonics to 3-4 combinations, and 5-6 combinations to 4-7 combinations. In

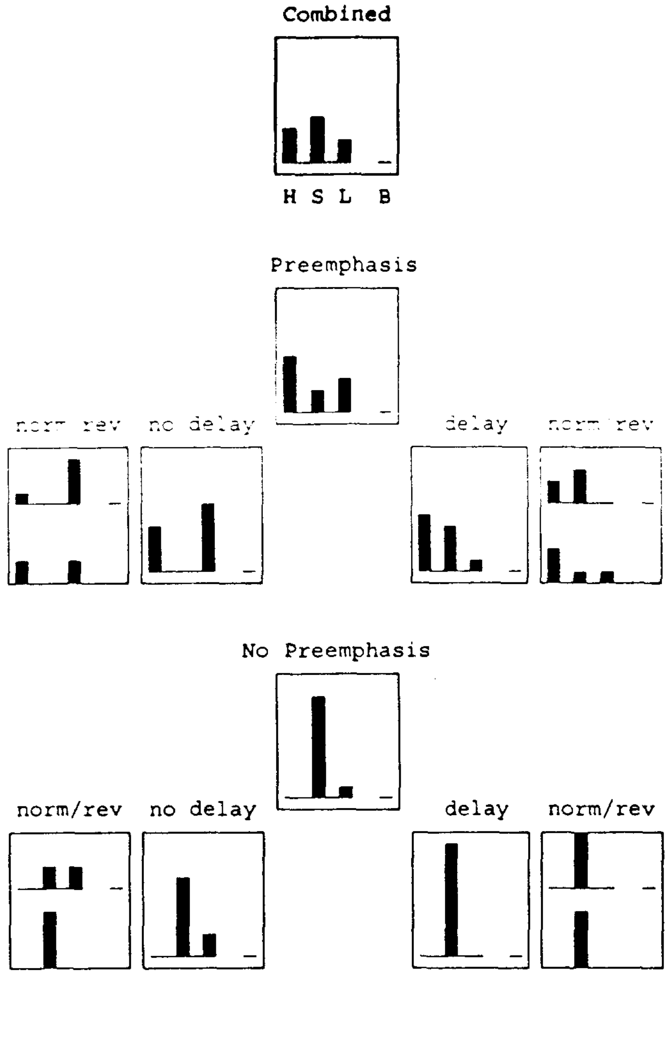


Figure 8. Fundamental Tracking Comparisons, High Frequency
1 Stimulus pair, n = 28

the former cases there were parallel changes in frequency spectrum and place of stimulation, while in the latter cases both average spectrum and place of stimulation were held constant in going from adjacent to widely spaced harmonic pairs. In both cases the results were strongly dependent on the presence of a delay for the higher fundamental. For the lower fundamental (392 Hz), the 3-4 combination was heard as lower in pitch with or without delay (91%), with the 5-6-to-4-7 comparison depending strongly on whether there was a delay.

Perception of a semitone interval as represented by various harmonic subsets. The salience of the pitch difference between the sequentially presented G and G# can be assessed also with various combinations of complex cues in the absence of channel changes. A first sequence of such comparisons would test the patient's ability to detect a pitch difference between G-196 and G#-208 with the following partials provided in both cases:

harmonic 2 alone
3 alone

4 alone
3 and 4 together (same channel)
2, 3, and 4
2 and 3 (different channels)
2 and 4 (different channels)
5 alone
6 alone
5 and 6 (same channel)
etc.

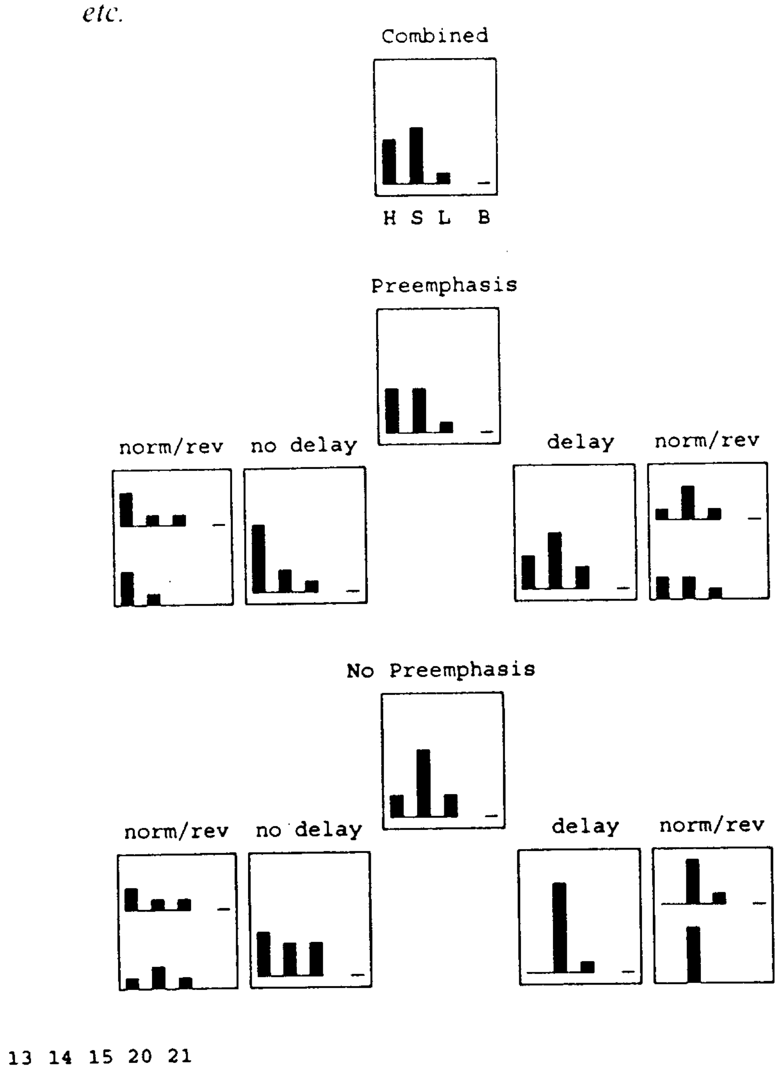


Figure 9 Semitone Sequences: Single Harmonics
5 Stimulus pairs, n = 140

While the number of presentations in our pilot survey varies widely across the various categories within this sequence, some intriguing patterns have been detected. There is a strong statistical similarity between results for five stimulus pairs comparing the pitch of single harmonics of the two fundamentals (harmonics 2, 3, 4, 5, and 6; Figure 9) and results for four pairs comparing non-adjacent harmonic pairs presented in separate channels (harmonics 2 and 4, 3 and 5, 4 and 6, and 4 and 8; Figure 10). Note the consistent strong effect of a delay between stimuli.

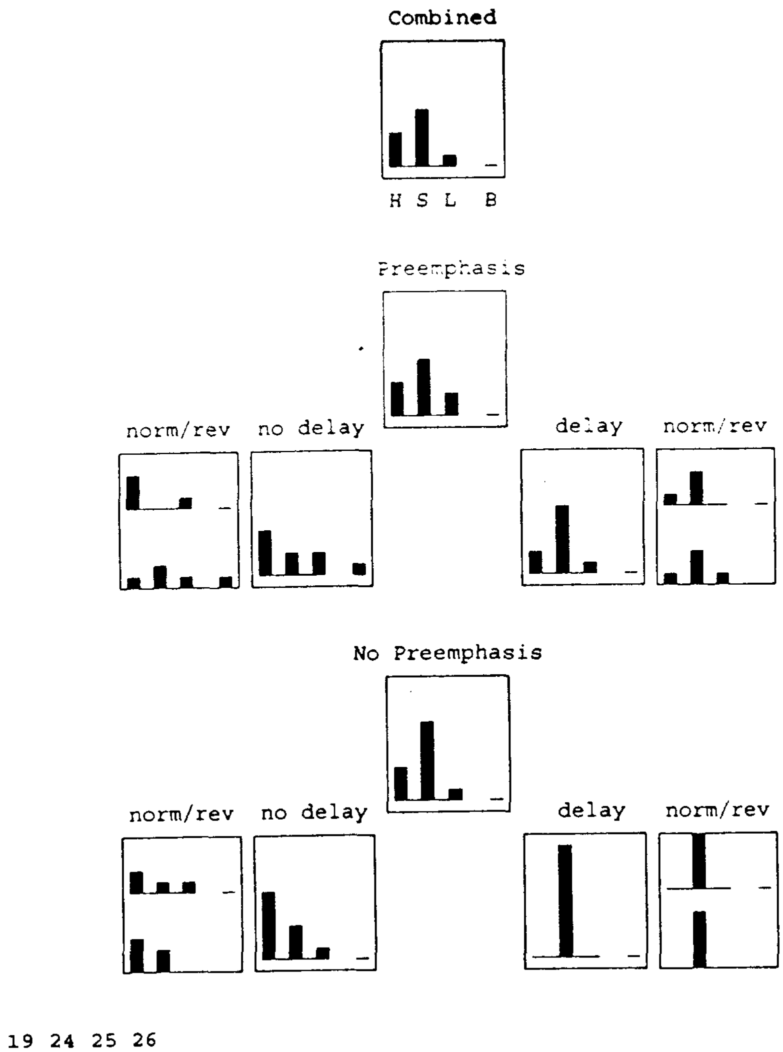
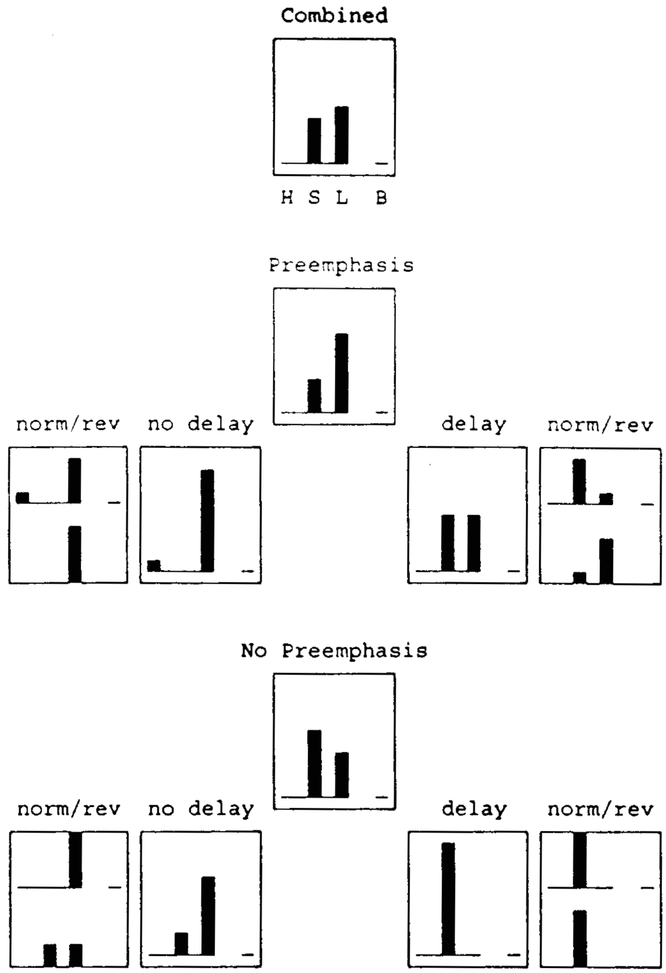


Figure 10. Semitone Sequences: Non-adjacent Harmonic Pairs
4 Stimulus pairs, n = 112

Single pairs of stimuli probing two additional categories from the same sequence, on the other hand, show quite different patterns. Figure 11 shows results for a pair of adjacent harmonics (5 and 6) conveyed in a **common** processor channel. While in some ways similar to the data in Figures 9 and 10, these results are notable for the appearance of a significant number of "both" responses and a for strong dependence on order of presentation in some circumstances. For a similar pair of adjacent harmonics (4 and 5) conveyed in **separate** processor channels, Figure 12 reveals many more "lower" responses, fewer "higher" responses, and no "both". Here strong order of presentation effects occur in different circumstances.

A distinctive structural feature of the stimulus pair represented by Figure 11 is the presence of beat cues at about 200 Hz in a channel conveying absolute frequencies near 1 kHz.

As will be seen in a later section of this report, there is substantial evidence that relatively low frequency beats can serve as important pitch cues in complex tones.



23

Figure 11. Semitone Sequence: Adjacent Harmonics in a Common Channel
1 Stimulus pair, n = 28

Relative salience of conflicting cues: Another example of a potentially revealing comparison of perceived pitch for a sequence of complex tones includes the following two tones, meeting the 10 dB criterion for an 11 channel processor with 12th order bands (see Table 1):

Tone	Ch 3	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10	Ch 11
E^b-622	1	-	3	4	5	6	8
F-698	1	2	-	3	4	5	7

One interesting feature of this sequence is that, while the fundamental pitch of the second tone is two semitones higher, the change in place information involves stimulating a lower channel (6)

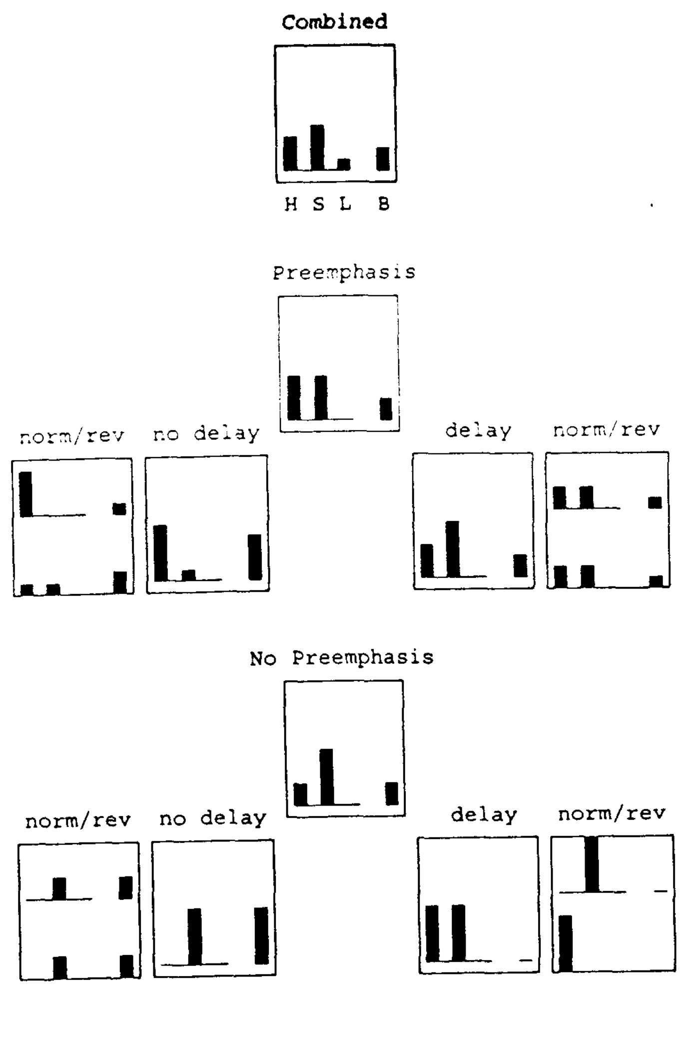


Figure 12. Semitone Sequence: Adjacent Harmonics in Separate Channels
1 Stimulus pair, n = 28

instead of a higher one (7). The overall extent of place information, the number of channels stimulated, and the number of harmonics conveyed all remain constant. While the fundamental frequency in channel 3 increases, the frequencies represented in channels 8 through 11 each decrease. (Since the harmonic number conveyed decreases in each of these channels, however, the envelope amplitudes also increase.) The structure of this stimulus pair is shown at the top of Figure 13. For comparison, the same sequence may be repeated without any use of channel 6 or 7 and with the further removal of the fundamentals from channel 3. Since subject SR2 was known to be able to discriminate among unusually high rates, one might expect the 622-698 Hz increase in channel 3 in the first two of these cases to compete with the other potential cues that suggest a pitch decrease, perhaps resulting in some "both" responses. [The first-order envelope smoothing filters could convey some temporal information at those rates.] Further, one might expect more such responses in the second case, with the removal of the potential place of stimulation cue for decreasing pitch. The third case appears to offer no cues favoring a pitch

Harms	f_h	Chans	f_b
1	622	3	
3	1866	7	
4	2489	8	
5	3111	9	
6	3733	10	
8	4978	11	

Harms	f_h	Chans	f_b
1	698	3	
2	1396	6	
3	2095	8	
4	2793	9	
5	3492	10	
7	4889	11	

E^b 622

F 698

f_{av} =	2800	\	2561
c_{av} =	8.0	-	7.8
c_{hw} =	5.9	-	6.0
f_b =		-	

3013-68

321-57

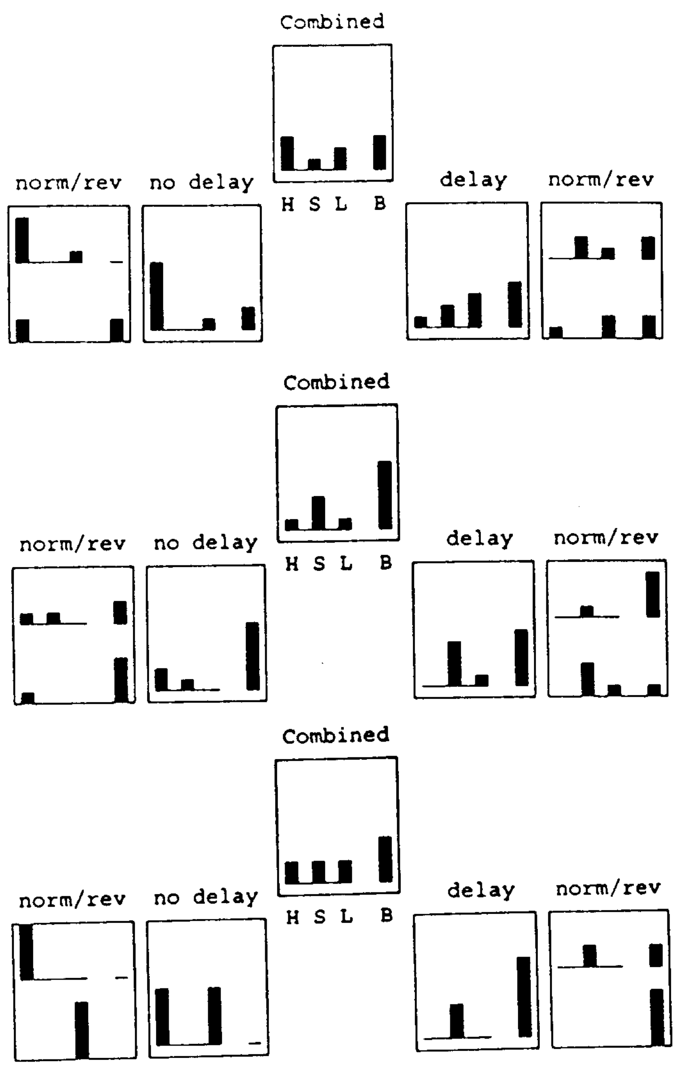


Figure 13. Relative Salience of Conflicting Cues: Three Cases
Each case: 1 Stimulus pair and n = 20

increase, other than the harmonic structure of the partials, all of which have absolute frequencies above 2 kHz. The survey results for those three cases are shown in lower panels of Figure 13. [Only the standard processor design with preemphasis was used in our 11 channel survey.]

The number of "both" responses is indeed maximum in the second case, increasing substantially with removal of the channel change between cases 1 and 2. A substantial number of such responses persist in case three, however, where the fundamentals have been removed as well. Interestingly, in case 3 they occurred only for presentations with delay. A particularly strong contrast can be found between the first two cases in the no-delay condition, where the responses change from predominantly "higher" to predominantly "both". There is some evidence for order of presentation effects as well.

Some examples in which low frequency intrachannel beats are among the competing potential cues will be included in a later section of this preliminary report.

Perception of chromatic intervals between sequentially presented complex tones: There is a handy set of nine complex tones, also for the 11-channel, 12th-order, 10 dB criteria (Table 1), that can support a preliminary survey of a patient's percepts of sequentially presented complex tones whose fundamental pitches differ by various musical intervals. Harmonics 3, 4, 5, and 8 meet the criteria for all nine tones. The six tones shown in boldface type have harmonic 2 available as well:

Tone	Fundamental
1	E-165Hz
2	**G#-208**
3	A-220
4	**C-262**
5	D-294
6	**F-349**
7	**A-440**
8	**C#-554**
9	**D-587**

No two partials are presented in the same channel for any of these conditions. The channels included are:

		Channels Utilized for Harmonics				
Tone		(H2)	H3	H4	H5	H8
1	E		2	3	4	6
2	**G#**	**1**	3	4	5	7
3	A		3	4	5	7
4	**C**	**2**	4	5	6	8
5	D		4	5	6	8

6	**F**	**3**	5	6	7	9
7	**A**	**4**	6	7	8	10
8	**C#**	**5**	7	8	9	11
9	**D**	**5**	7	8	9	11

and the available complex harmonic intervals include the following (comparisons involving two tones both of which have the second harmonic available are shown in boldface type):

Interval(s)	Tone pair(s) available for comparisons
octaves	3 - 7 and 5 - 9
perfect fifth	5 - 7
perfect fourths	1 - 3, 3 - 5, **4 - 6,** and **7 - 9**
major thirds	1 - 2, **2 - 4, 6 - 7**, and **7 - 8**
minor thirds	3 - 4 and 5 - 6
minor sixths	1 - 4, 3 - 6, and **6 - 8**
major sixths	**2 - 6,** 4 - 7, and **6 - 9**
major second	4 - 5
minor seconds	2 -3 and **8 - 9**
minor seventh	1 - 5
major seventh	5 - 8
tritone	2 - 5

Depending on the place and periodicity discrimination abilities of the patient, comparisons among these complex tones could be used to assess (1) the ability to detect sequential pitch differences of various magnitudes and in various absolute pitch ranges, (2) the ability to rank such sequential intervals by width, (3) the ability to recognize like sequential intervals at different absolute pitches, and perhaps even (4) the ability to make consonance/dissonance judgments analogous to those of normal hearing subjects.

For those not familiar with the standard musical terminology and notations, the following list displays each chromatic interval, its abbreviation, the number of notational semitones spanned by it, and the frequency ratio of the pure (harmonically exact) interval (Rossing, 1990):

Interval	Abbrev.	Semitones	Freq. Ratio
octave	P8	12	2/1
perfect fifth	P5	7	3/2
perfect fourth	P4	5	4/3
major third	M3	4	5/4
minor sixth	m6	8	8/5
minor third	m3	3	6/5

major sixth	M6	9	5/3
major second	M2	2	
minor seventh	m7	10	
minor second	m2	1	
major seventh	M7	11	
tritone	T	6	

For 6-channel, 6th-order [or 12th-order] processors and the 10 dB criterion (Table 5), there is a similar set of eight complex tones that might be useful in preliminary pitch perception studies. Harmonics 2, 3, 5, and 8 meet the criteria for all these tones. Those shown in boldface type are also available with harmonics 2, 3, 5, and 7 for comparison:

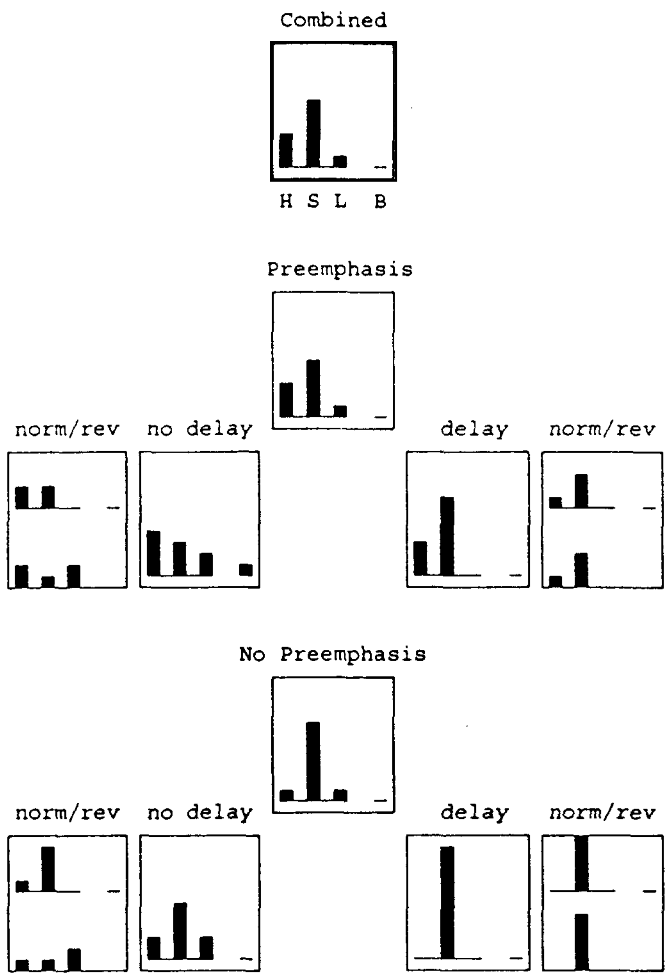
Tone	Fundamental
1	G$^{\#}$-208 Hz
2	A-220
3	**B^{b}-233**
4	E-330
5	**F-349**
6	**F$^{\#}$-370**
7	**C$^{\#}$-554**
8	**D-587**

This set can support studies of place information salience for some relatively small and relatively large harmonic intervals between sequentially presented complex tones. The five tones for which both harmonics 7 and 8 meet the criteria also provide the option of comparison tones that provide a fundamental frequency beat in the highest channel. The channel assignments are:

		Channels Utilized for Harmonics				
Tone		H2	H3	H5	(H7)	H8
1	G$^{\#}$	1	2	3		4
2	A	1	2	3		4
3	**B^{b}**	1	2	3	4	4
4	E	2	3	4		5
5	**F**	2	3	4	5	5
6	**F$^{\#}$**	2	3	4	5	5
7	**C$^{\#}$**	3	4	5	6	6
8	**D**	3	4	5	6	6

and the available complex harmonic intervals include (boldface indicates that both tones of a pair support 2-3-5-7 and single-channel 7-8 comparisons as well as 2-3-5-8):

Interval(s)	Tone pair(s) available for comparisons
minor seconds	1 - 2, 2 - 3, 4 - 5, **5 - 6**, and **7 - 8**
major seconds	1 - 3 and 4 - 6
tritone	3 - 4
perfect fifths	2 - 4, **3 - 5**, and **6 - 7**
minor sixths	1 - 4, 2 - 5, **3 - 6**, **5** - 7, and **6 - 8**
major sixths	1 - 5, 2 - 6, 4 - 7, and **5 - 8**
minor sevenths	1 - 6 and 4 - 8



34 35 36 37 40

Figure 14. Sequential 4-Harmonic Intervals: Minor Seconds
5 Stimulus pairs, n = 140

A substantial number of stimulus pairs in our pilot survey were devoted to assessing the salience and consistency of these sequential musical intervals. The results divide very clearly into two groups -- the seconds (major and minor) and the others. Displays are provided for the five minor second sequences (semitones) in Figure 14, for the two major seconds (wholetones) in Figure 15, and a combined 21 pairs including the tritone, fifths, sixths, and sevenths in Figure 16.

Most of the sequential second pairs were perceived as "same" with most of the remainder receiving a "higher" response (Figures 14 and 15). The responses were predominantly "same" when there was no preemphasis, and "higher" responses were more likely when there was no delay. More detailed and extensive testing of these narrow intervals is needed. Anecdotally, differences were frequently noted within these and other semitone interval pairs, but often described in terms of timbre rather than pitch.

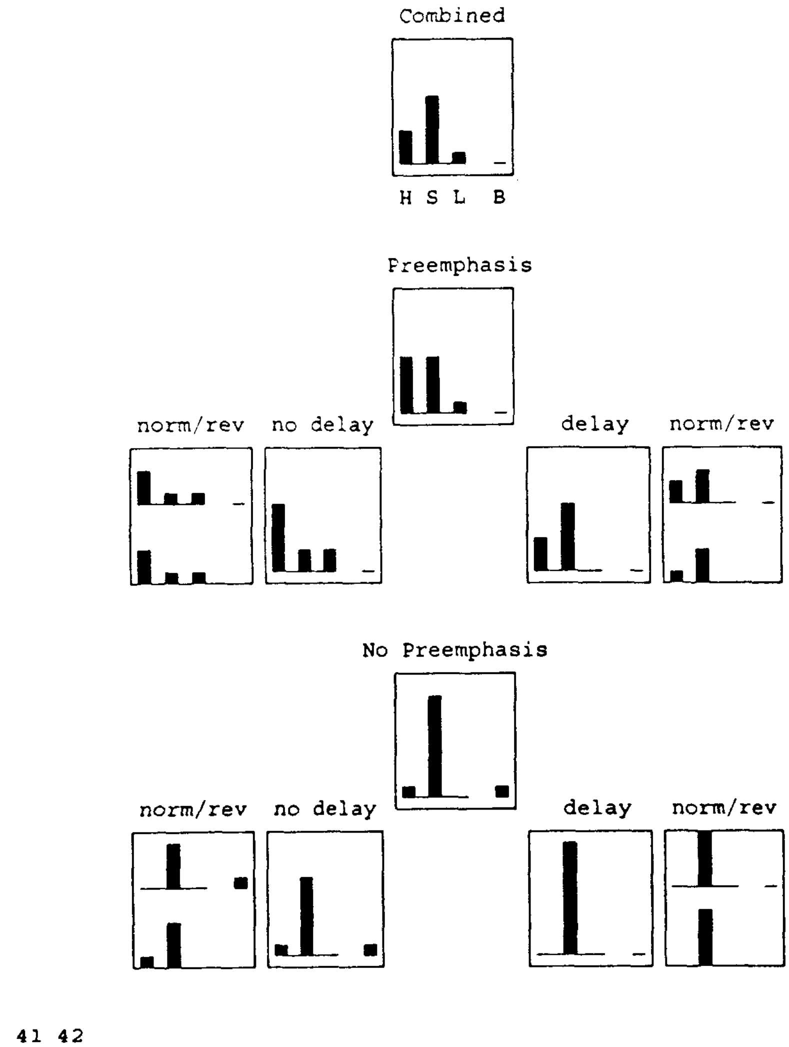


Figure 15. Sequential 4-Harmonic Intervals: Major Seconds
2 Stimulus pairs, n = 56

Results for the tritone and wider intervals (Figure 16) indicate no ambiguity at all in their detection. Two types of further studies are indicated for these sequential intervals. First, we should try introducing partials that do **not** meet our exclusivity criteria and look for any decrease in the saliency of the pitch changes. Second, we are free to proceed to studies of consonance and

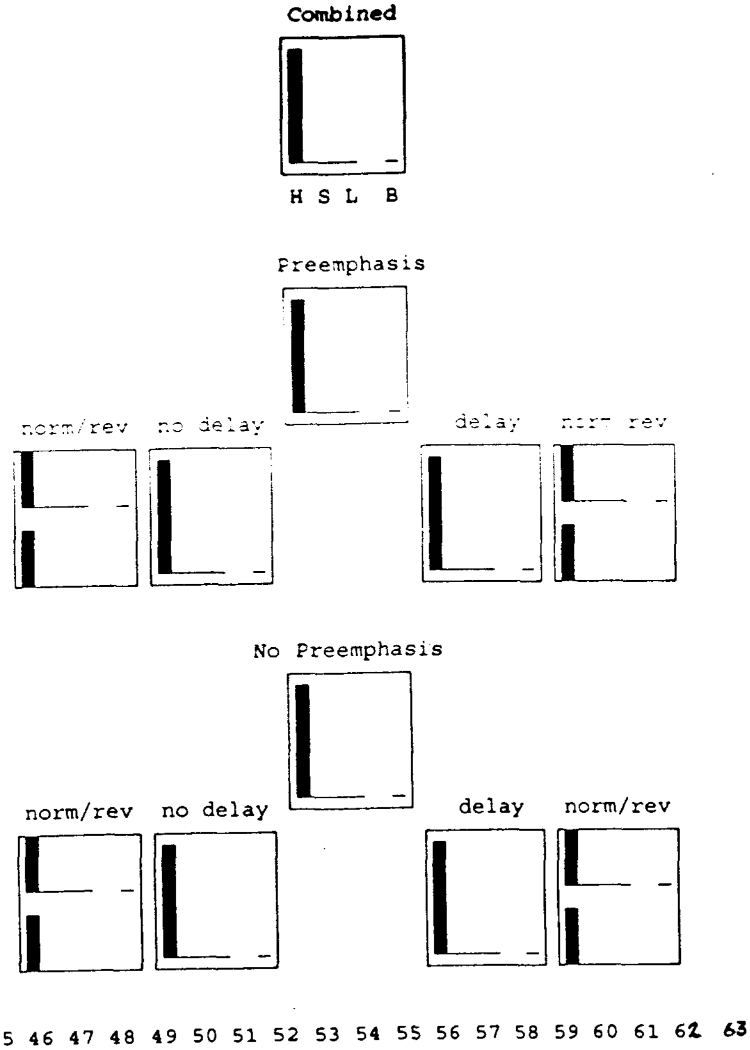


Figure 16. Sequential 4-Harmonic Intervals: Tritones through Sevenths
21 Stimulus pairs, n = 588

dissonance judgments and tone timbre comparisons using these stimuli, without any concerns as to detection of the existence and sign of pitch differences. In our preliminary anecdotal studies with these stimuli SR2 showed strong and consistent percepts of timbre and relative consonance. It was not unusual for him to volunteer a correct identification for a musical interval (most often a consonant interval). There were instances of additional information apparently being gleaned from more complex presentation sequences -- for instance SR2's volunteering, accurately, that while he could not be sure of the exact interval between the most recent two stimuli, he was confident that it was the same interval as the last pair, only transposed up a semitone. At times he spontaneously would sing candidate pitches and intervals, as though to himself, while considering his anecdotal responses. The spontaneous nature of this practice (and the subject's shyness about it) prevented us from gathering any meaningful statistical assessment of his accuracy in these attempts, but several of our strong impressions may be worth mentioning, pending future studies: (1) SR2 was no less likely to sing pitches when he could not monitor himself via his speech processor than when he could. (The experimenter frequently would open the subject's microphone for anecdotal discussion, but the microphone signal was never available during presentation of stimulus pairs.) (2) While it was not at all unusual for SR2 to sing intervals and absolute pitches accurately, he seemed somewhat **more** likely to do so when he could **not** monitor his own voice via the processor, and on his first attempt rather than after repeated (especially when monitored) attempts. Careful exploration of these preliminary indications is planned.

The limitations imposed by 6th-order bandpass filter edges become most apparent when we attempt to construct tests to assess the salience of the periodicity information available when adjacent harmonics beat within the same channel. A search for instances of the same two harmonics being available under these 6-channel, 6th-order, 10 dB criteria within the same channel for two different fundamental pitches, finds the following:

Tone	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
B-123		5,6				
C-131		5,6				
$C^{\#}$-139			7,8			
D-147			7,8			
B^{b}-233				7,8		
B-247				7,8		
F-349					7,8	
$F^{\#}$-370					7,8	
$G^{\#}$-415					6,7	
A-440					6,7	
$C^{\#}$-554						7,8
D-587						7,8
E^{b}-622						7,8
E-659						6,7
F-698						6,7
$F^{\#}$-740						6,7

Thus we have nine distinct combinations of adjacent harmonic pair and channel within which minor second comparisons may be made, and two such combinations that will support major second comparisons. The fundamental pitches involved (and therefore the adjacent harmonic beat rates) range from 123 to 740 Hz. However, a search for instances in which the same pairs of adjacent harmonics are conveyed in *two different* channels -- ideally over the same range of fundamental frequencies -- will fail to reveal any such complementary opportunities involving harmonics 5 through 8. The best such comparison would involve harmonics 4 and 5, conveyed separately in channels 2 and 3 for G-196 and together in channel 2 for E^b-156, but with no equivalent case(s) for other nearby fundamentals.

The use of 12th-order filters in a 6 channel processor under the 10 dB criterion (Table 3) substantially facilitates the experimental design process. Following are tabulations of groups of tones that provide three different relationships between represented pairs of adjacent harmonics (harmonics differing in frequency by the fundamental) and channel assignment: (1) Table 8: a group of tones in which the *same* adjacent pair of harmonics are conveyed in the *same* single channel, (2) Table 9: a group of tones in which the *same* adjacent pair of harmonics are conveyed in *different* pairs of channels, and (3) Table 10: a group of tones in which *different* adjacent pairs of harmonics are conveyed in the *same* single channel.

Scanning these three arrays for various small chromatic intervals between available tones' fundamental frequencies yields the following number of instances in each case:

		Number of Tone Pairs Available by Chromatic Interval			
Harmonic Pair	Channel	minor 2nd	major 2nd	minor 3rd	major 3rd
same	same	53	30	13	2
same	different	26	11	3	0
different	same	23	35	50	59

There appear to be enough exemplars, at least for major and minor second intervals, to support a systematic statistical study of the salience with which sequential complex tone pitch differences may be conveyed in various ways via adjacent harmonics -- if such a study is indicated by less formal preliminary results.

In looking for efficient ways in which to obtain such preliminary data, it is helpful to organize the available comparison intervals from the three arrays into the two tools displayed below as Tables 11 and 12.

Table 8

Same Harmonic Pairs in Same Single Channel

Harmonic Pair	Channel	Fundamentals of Available Tones
3-4	1	B-123, C-131
	2	G-196, $G^\#$-208
	3	E^b-311, E-330
	6	E^b-1245, E-1319
4-5	2	D-147, E^b-156, E-165
	3	B^b-233, B-247, C-262
	4	$F^\#$-370, G-392, $G^\#$-415
	5	D-587, E^b-622
	6	B^b-932, B-988, C-1047
5-6	2	B^b-117, B-123, C-131, $C^\#$-139
	3	$F^\#$-185, G-196, $G^\#$-208, A-220
	4	D-294, E^b-311, E-330
	5	B^b-466, B-494, C-513
	6	$F^\#$-740, G-784, $G^\#$-831, A-880
6-7	2	A-110, B^b-117
	3	E^b-156, E-165, F-175, $F^\#$-185
	4	B-247, C-262, $C^\#$-277, D-294
	5	G-392, $G^\#$-415, A-440, B^b-466
	6	E^b-622, E-659, F-698, $F^\#$-740
7-8	3	C-131, $C^\#$-139, D-147, E^b-156, E-165
	4	$G^\#$-208, A-220, B^b-233, B-247
	5	E-330, F-349, $F^\#$-370, G-392
	6	C-523, $C^\#$-554, D-587, E^b-622, E-659
interval examples:		<-minor 2nd-> <---major 2nd-----> <---------------major 3rd--------------->

Table 9

Same Harmonic Pairs in Separate Channels

Harmonic Pair	Channel Pair	Fundamentals of Available Tones
3-4	1-2	D-147, E^{b}-156, E-165, F-175
	2-3	B^{b}-233, B-247,C-262, $C^{\#}$-277
	3-4	$F^{\#}$-370, G-392, $G^{\#}$-415, A-440
	4-5	D-587, E^{b}-622, E-659
	5-6	B^{b}-932, B-988, C-1047
4-5	1-2	B^{b}-117, B-123, C-131
	2-3	$F^{\#}$-185, G-196, $G^{\#}$-208
	3-4	D-294, E^{b}-311, E-330
	4-5	B^{b}-466, B-494
	5-6	$F^{\#}$-740, G-784
5-6	2-3	E^{b}-156, E-165
	3-4	B-247, C-262
	4-5	G-392, $G^{\#}$-415
6-7	2-3	C-131, $C^{\#}$-139
	3-4	$G^{\#}$-208, A-220
7-8	(none)	

Table 10

Different Harmonic Pairs in Same Single Channel

Chan	Harm. Pair	Fundamentals of Available Tones									
2	6-7	A	B^b								
	5-6		B^b	B	C	$C^{\#}$					
	4-5						D	E^b	E		
	3-4									G	$G^{\#}$
		110	117	123	131	139	147	156	165	196	208
3	7-8	C	$C^{\#}$	D	E^b	E					
	6-7				E^b	E	F	$F^{\#}$			
	5-6							$F^{\#}$	G	$G^{\#}$	A
		131	139	147	156	165	175	185	196	208	220
	4-5	B^b	B	C							
	3-4				E^b	E					
		233	247	262	311	330					
4	7-8	$G^{\#}$	A	B^b	B						
	6-7				B	C	$C^{\#}$	D			
	5-6							D	E^b	E	
		208	220	233	247	262	277	294	311	330	
	4-5	$F^{\#}$	G	$G^{\#}$							
	3-4				B						
		370	392	415	494						
5	7-8	E	F	$F^{\#}$	G						
	6-7				G	$G^{\#}$	A	B^b			
	5-6							B^b	B	C	
		330	349	370	392	415	440	466	494	523	
	4-5	D	E^b								
	3-4			$G^{\#}$							
		587	622	831							
6	7-8	C	$C^{\#}$	D	E^b	E					
	6-7				E^b	E	F	$F^{\#}$			
	5-6							$F^{\#}$	G	$G^{\#}$	A
		523	554	587	622	659	698	740	784	831	880
	4-5	B^b	B	C							
	3-4				E^b	E					
		932	988	1047	1245	1319					

examples: <--major 3rd---> <-----------major 3rd--------->
<--major 3rd--->

Table 11

Same Harmonic Pair: Single Channel and Channel Pair Assignments

Harm. Pair	Single Ch.	Ch. Pair	m2's	M2's	m3's	fund. freq. range
3-4:	1		1			123-131
		1-2	3	2	1	147-175
	2		1			196-208
		2-3	3	2	1	233-277
	3		1			311-330
4-5:	2		2	1		147-165
		2-3	2	1		185-208
	3		2	1		233-262
		3-4	2	1		294-330
	4		2	1		370-415
		4-5	1			466-494
	5		1			587-622
		5-6	1			740-784
	6		2	1		932-1047
5-6:	2		3	2	1	117-139
		2-3	1			156-165
	3		3	2	1	185-220
		3-4	1			247-262
	4		2	1		294-330
		4-5	1			392-415
	5		2	1		466-513
6-7:	2		1			110-117
		2-3	1			131-139
	3		3	2	1	156-185
		3-4	1			208-220
	4		3	2	1	247-294

Table 12

Assignment of Different Harmonic Pairs to Same Channel

Channel	Harmonic Pairs	m2's	M2's	m3's	M3's	fund. freq. range
2:	5-6 and 6-7	2	2	2	1	110-139
	4-5 and 5-6	1	2	3	3	117-165
	3-4 and 4-5	1	2	2		147-208
3:	6-7 and 7-8	3	4	4	3	131-185
	5-6 and 6-7	2	3	4	3	156-220
	4-5 and 5-6	1	2	3	3	185-262
	3-4 and 4-5			1	2	247-330
4:	6-7 and 7-8	2	3	4	3	208-294
	5-6 and 6-7	2	3	3	2	247-330
	4-5 and 5-6		1	2	3	294-415
	3-4 and 4-5			1	1	392-494
5:	6-7 and 7-8	2	3	4	3	330-466
	5-6 and 6-7	2	3	3	2	392-523
	4-5 and 5-6		1	2	2	466-622
6:	6-7 and 7-8	3	4	4	3	523-740
	5-6 and 6-7	2	3	4	3	622-880
	4-5 and 5-6	1	2	3	3	740-1047
	3-4 and 4-5			1	2	988-1319

As an example of the use of such tools, we can construct a minor second sequential interval discrimination survey in two parts. The first part will use adjacent harmonic pairs 4-5 and 5-6 and channels 2 and 3, choosing the lowest available fundamental frequencies in each condition. The second part will use harmonic pairs 5-6 and 6-7 and channels 3 and 4, choosing the highest available fundamental frequencies in each condition.

adjacent harm. pair	single channel	channel pair	fundamental frequencies for the sequential intervals (m2's)
4-5	2		D-147,E^b-156
4-5	3		B^b-233, B-247
4-5		2-3	F$^\#$-185, G-196
5-6	2		B^b-117, B-123
5-6	3		F$^\#$-185, G-196
5-6		2-3	E^b-156, E-165
4-5 and 5-6	2		D-147, C$^\#$-139
4-5 and 5-6	3		B^b-233, A-220
			part one fundamental range: 117-247
5-6	3		G$^\#$-208, A-220
5-6	4		E^b-311, E-330
5-6		3-4	B-247, C-262
6-7	3		F-175, F$^\#$-185
6-7	4		C$^\#$-277, D-294
6-7		3-4	G$^\#$-208, A-220
5-6 and 6-7	3		G-196, F$^\#$-185
5-6 and 6-7	4		E^b-311, D-294
			part two fundamental range: 175-330

Each part of this survey consists of playing eight pairs of complex tones for the patient and determining whether the patient can (1) detect a pitch difference between the tones of each pair and (2) identify which of the pair has the higher pitch. Each tone is a combination of two adjacent harmonics. The fundamental frequencies of each pair of tones (and, hence, the difference in frequency between the two adjacent harmonics of each of those frequencies) differ by a minor second (an equal-tempered musical semitone) in each case. The two tones of each pair are presented sequentially. The first three pairs of tones all use the same pair of harmonics, but present those two harmonics (1) both to one channel, (2) both to an adjacent channel, (3) one to each of those channels. The next three pairs of tones repeat that sequence for the same two channels, but a different pair of harmonics. Each of the final two pairs of tones presents one of the pairs of adjacent harmonics and then the other, both to the same single channel. This is done for each of the two channels being investigated. This overall stimulus structure was also built for a second pair of channels, as shown above.

Such surveys should be useful in determining whether such distinctions are salient for electrically stimulated patients and, if so, for what magnitude of sequential interval and in what fundamental frequency range. Armed with that knowledge and the tools displayed above, a more thorough statistical measurement can be designed.

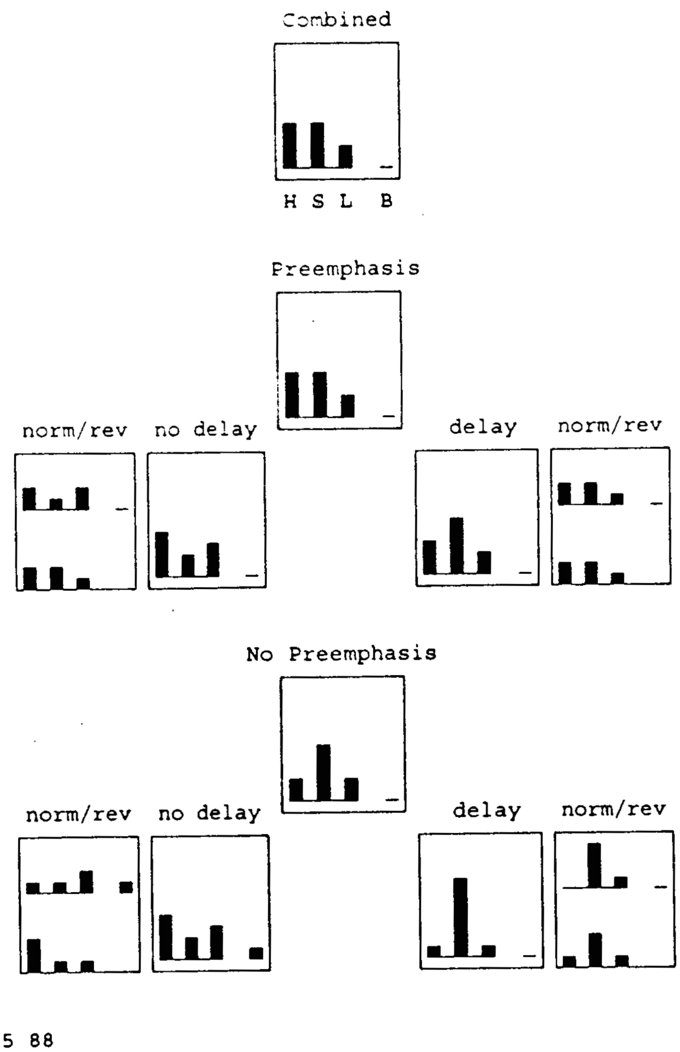


Figure 17. Semitone Sequences: Same Harmonic Pairs to Same Channel Pairs
4 Stimulus pairs, n = 112

Figure 17 displays survey results for the four stimulus pairs in which the same pair of adjacent harmonics was delivered to the same pair of channels. In these cases the only potential fundamental frequency cue would be in the form of interchannel beating. No one result is favored overall, but there are clearly more "same" responses when a delay is present and more "same" responses for the processor without the normal preemphasis. No order of presentation effects are seen.

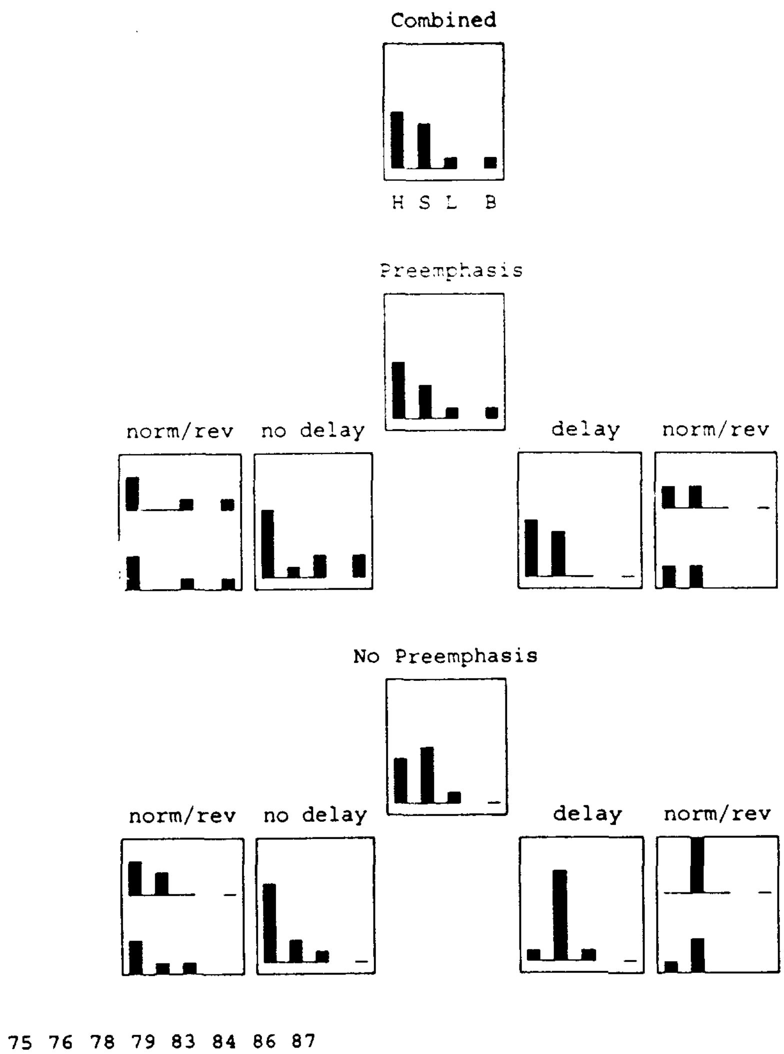


Figure 18. Semitone Sequences: Same Harmonic Pairs to Same Single Channels
8 Stimulus pairs, n = 224

In Figure 18 we have collected the results for eight other stimulus pairs representing the same range of harmonics, channels, and fundamental frequencies. In each of these cases, however, the same pair of adjacent harmonics was delivered to the same single channel, making intrachannel beats available as a potential pitch cue at the fundamental frequencies. Here "higher" responses predominate when there is no delay. Adding a delay results in more "same" responses, and the combination of no preemphasis and a delay again eliminates discrimination.

Taken together these preliminary findings suggest that intrachannel beating in a CIS processor, in a minimal context and with beats conveying frequencies in the 150 - 350 Hz range, can support semitone (minor second) pitch distinctions. Note that the harmonic components input to the processors in these cases ranged roughly from 600 to 2000 Hz in absolute frequency (fourth harmonic of the lower D to the seventh harmonic of the upper D).

Simultaneous Complex Tone Intervals
Harmonic Partials of Two Distinct Fundamentals

The previous section's tests have been concerned with whether a patient might be able to make absolute pitch judgments on the basis of adjacent harmonics within complex tones of a single fundamental, and with differences in such an ability depending on whether the adjacent harmonics were conveyed via a common channel of stimulation or via separate channels. Wherever adjacent partials were presented to a common channel, the beat rate created in that channel was at the fundamental frequency of the complex tone -- whether or not the fundamental was actually present as a partial -- or some larger multiple of that frequency.

In this section we turn to the perception of simultaneous complex tone intervals , *i.e.* complex tones whose partials include harmonics of two distinct fundamentals. Again we shall focus initially on the salience of cues resulting from adjacent partials and on the various place and periodicity roles played by such partials. In this case, however, the beat frequencies between pairs of partials conveyed in common channels will vary widely, with certain patterns being characteristic of particular ratios between fundamental frequencies. Many of the adjacent partial beat frequencies will be relatively small fractions of the lower fundamental and thus more accessible as periodicity information via electrical stimulation.

All of the examples in the previous section used equal-tempered intervals between sequentially presented complex tone fundamentals and exact harmonic relationships among the partials of each complex tone. In this section we shall identify the lower fundamental frequency of a simultaneous interval in terms of an equal-tempered scale, but require an exact harmonic interval between the two fundamentals in order to convey the frequency degeneracies characteristic of the exact complex interval's beat frequency pattern.

We begin by examining the distinctive patterns among adjacent partials -- and the potential beat frequencies between them -- for the five most consonant intervals between complex tone fundamentals: octave, perfect fifth, perfect fourth, major third, and minor third (Rossing, 1990). In each case we shall label the partials in terms of frequency ratios with respect to the lower tone fundamental. For the octave we have:

Low	1	2	3	4	5	6	7	8
High		2		4		6		8
Intvl		1	1	1	1	1	1	1

The third line lists the intervals between adjacent partials, also in terms of the lower tone fundamental. In the case of a complex tone octave, the frequency difference between each pair of adjacent partials is simply equal to the lower tone's fundamental.

Now, for a pair of complex tones whose fundamentals are separated by a perfect fifth we have:

Low	1		2	3	4		5	6	7		8
High		1.5		3		4.5		6		7.5	
Intvl		.5	.5	1	1	.5	.5	1	1	.5	.5

Half of the adjacent partial pairs are separated by the fundamental frequency, while the other half differ by one half that frequency.

For the interval of a perfect fourth between the fundamentals of two complex tones we note this pattern:

Low	1		2		3	4	5		6		7
High		1.33		2.67		4		5.33		6.67	
Intvl		.33	.67	.67	.33	1	1	.33	.67	.67	.33

One third each of the adjacent pairs are separated by the lower tone fundamental, one third of that frequency, and two thirds of that frequency.

In the case of a complex tone major third, the pattern of adjacent partials takes the following form:

Low	1		2		3		4	5	6		7
High		1.25		2.5		3.75		5		6.25	
Intvl		.25	.75	.5	.5	.75	.25	1	1	.25	.25

and so on, with one quarter each of the adjacent parital pairs separated by the lower tone fundamental, one fourth of that frequency, one half of it, and three fourths of it.

Finally, for an interval of a minor third between complex tone fundamentals, the pattern becomes:

Low	1		2		3		4		5	6	7
High		1.2		2.4		3.6		4.8		6	
Intvl		.2	.8	.4	.6	.6	.4	.8	.2	1	1

With the adjacent partial pairs divided into five groups, corresponding to frequency differences of the lower tone fundamental, and one through four fifths of that amount.

Thus, as we go from the octave to the minor third in this sequence, we find progressively larger numbers of distinct frequency differences between adjacent partials, including progressively lower potential beat frequencies between such partials. Beating between adjacent partials at such frequencies may well be salient to electrically-stimulated auditory implant patients even when the absolute frequencies of the partials are far too high to provide usable periodicity information.

As mentioned earlier, the "normal" order for our stimulus pairs involving simultaneous multi-fundamental intervals was from the wider interval between fundamentals to the narrower. Both stimuli of each pair were based on the same lower fundamental, with the upper fundamental of the second stimulus being lower than that of the first (for instance, a major third followed by a minor third sharing the same lower fundamental).

Ha	Hb	f_h	Chans	f_b
	2	617	2	
			2	123
3		740	2	

Ha	Hb	f_h	Chans	f_b
	2	592	2	
			2	148
3		740	2	

B	247	E^b	5/4

B	247	D	6/5

f_{av} =	679	\	666
c_{av} =	2.0	-	2.0
c_{hw} =	2.0	-	2.0
f_b =	123	/	148

I1418a I1417a

Ha	Hb	f_h	Chans	f_b
7		1728	4	
			4	123
	6	1852	4	

Ha	Hb	f_h	Chans	f_b
8		1975	4	
			4	98
	7	2074	4	

B	247	E^b	5/4

B	247	D	6/5

f_{av} =	1790	/	2025
c_{av} =	4.0	-	4.0
c_{hw} =	4.0	-	4.0
f_b =	123	\	98

I1418c I1417e

Figure 19. Complex Major and Minor Thirds: Conflicting Cues

Figure 19 shows the structure of two stimulus pairs based on a *major third* (a frequency ratio of 5 to 4) in the first tone of each pair and a *minor third* (ratio of 6 to 5) in the second. In musical notation, the left interval is between fundamentals B and E^b and the right between B and D in each case. The harmonics of each fundamental are tabulated separately.

In the upper pair of Figure 19 the third harmonic of the lower fundamental and the second of the higher are chosen in each case, all conveyed by processor channel 2. The average frequency f_{av} declines a bit and place of stimulation is unchanged. Only the beat frequency rises -- from 123 to 148 Hz. SR2 heard the second (right-hand) tone as higher 100% of the time, and anecdotally reported that it was higher "by a semitone".

Pitch change percepts that correspond to beat frequency changes -- even in the face of conflicting cues -- form a strong pattern in our pilot studies. In the second example of Figure 19, pairs of higher harmonics of the same fundamentals stimulate channel 4. Here f_{av} increased, but the subject's percept followed the beat frequency's decline 96% of the time, anecdotally "down about a half step".

Ha	Hb	f_h	Chans	f_b
	4	1234	3	
5		1234	3	
6		1481	4	
			4	61
	5	1543	4	

Ha	Hb	f_h	Chans	f_b
	4	1185	3	
			3	49
5		1234	3	
	5	1481	4	
6		1481	4	

B 247	E^b 5/4	f_{av} =	1419	\	1300	B 247 | D 6/5
		c_{av} =	3.5	-	3.5	
		c_{hw} =	3.4	-	3.4	
		f_b =	61	\	49	

I1418b I1417b

Ha	Hb	f_h	Chans	f_b
7		1728	4	
			4	123
	6	1852	4	

Ha	Hb	f_h	Chans	f_b
7		1728	4	
			4	49
	6	1777	4	

B 247	E^b 5/4	f_{av} =	1790	\	1753	B 247 | D 6/5
		c_{av} =	4.0	-	4.0	
		c_{hw} =	4.0	-	4.0	
		f_b =	123	\	49	

I1418c I1417c

Ha	Hb	f_h	Chans	f_b
	6	1852	4	
			4	123
8		1975	4	

Ha	Hb	f_h	Chans	f_b
	6	1777	4	
			4	197
8		1975	4	

B 247	E^b 5/4	f_{av} =	1914	\	1876	B 247 | D 6/5
		c_{av} =	4.0	-	4.0	
		c_{hw} =	4.0	-	4.0	
		f_b =	123	/	197	

I1418d I1417d

Figure 20. Complex Major and Minor Thirds: Preemphasis Effects

In the uppermost part of Figure 20 is an example of changes in both the channel location of a beat and the beat frequency. Here there seems to be no conflict among potential pitch cues -- f_{av}, the beat frequency, and the apical migration of the beat all should signal a decrease in pitch. SR2 heard the right-hand tone as lower in pitch 81% of the time with preemphasis and always when there was no preemphasis. "Both" was the predominant alternative response, and SR2's anecdotal remarks included "Each sounds like two independent tones at times" and "strangest pair of the survey".

The remaining two stimulus pairs in Figure 20 correspond to another effect of preemphasis in our pilot survey data -- a rare but striking reversal of pitch ranking. In each of these two cases SR2's responses followed the change in beat frequency 100% of the time when preemphasis had been removed from the processor, but gave the opposite response (except for 5% "both" in each case) when the normal preemphasis was present. Such dramatic exceptions to otherwise strong patterns in the pilot data are themselves worthy of further study as they may well provide important clues as to the nature and limits of the underlying mechanisms. Anecdotally, the subject volunteered that the right-hand tone in the middle panel of this figure sounded "very dissonant". Initially -- apparently really impressed by that 49 Hz beat -- he described the right-hand tone as "much lower in pitch". After several repetitions of the pair, however, he revised his judgment to the two tones' being "a lot closer in pitch than [he] first thought". For the bottom stimulus pair in this figure, SR2 declared "the second is definitely higher".

Ha	Hb	f_h	Chans	f_b
4		987	3	
			3	123
	3	1111	3	

Ha	Hb	f_h	Chans	f_b
5		1234	3	
			3	81
	4	1316	3	

B	247	F#	3/2					B	247	E	4/3
				f_{av} =	1049	/	1275				
				c_{av} =	3.0	-	3.0				
				c_{hw} =	3.0	-	3.0				
				f_b =	123	\	81				

I1421a I1419a

Ha	Hb	f_h	Chans	f_b
	3	1111	3	
			3	123
5		1234	3	

Ha	Hb	f_h	Chans	f_b
5		1234	3	
			3	81
	4	1316	3	

B	247	F#	3/2					B	247	E	4/3
				f_{av} =	1173	/	1275				
				c_{av} =	3.0	-	3.0				
				c_{hw} =	3.0	-	3.0				
				f_b =	123	\	81				

I1421b I1419a

Figure 21. Complex Fifths and Fourths: Parameter Control

The remaining nine stimulus pair structures displayed in this report have two things in common. All are based on fundamental intervals of a *perfect fifth* (frequency ratio 3/2) on the left and a *perfect fourth* (4/3) on the right. In the statistical survey each of these examples had 100% unanimous responses for 28 presentations.

Figure 21 displays an example of the degree of control available in constructing these stimulus pairs based on complex intervals. While the first tone (left side) harmonics involved differ substantially between theses two stimulus pairs, most of our parametric values are held constant. SR2 heard the right-hand tone as lower in pitch in both cases.

Ha	Hb	f_h	Chans	f_b
	4	1481	4	
6		1481	4	
			4	246
7		1728	4	
			4	123
	5	1852	4	

Ha	Hb	f_h	Chans	f_b
6		1481	4	
			4	164
	5	1645	4	
			4	329
	6	1975	4	
8		1975	4	

B	247	F#	3/2

	Left		Right
f_{av} =	1687	/	1700
c_{av} =	4.0	-	4.0
c_{hw} =	4.0	-	4.0
f_b =	123	/	164
	246	/	329

B	247	E	4/3

I1421c I1419b

Ha	Hb	f_h	Chans	f_b
	4	1481	4	
6		1481	4	
			4	370
	5	1852	4	
			4	123
8		1975	4	

Ha	Hb	f_h	Chans	f_b
6		1481	4	
			4	164
	5	1645	4	
			4	329
	6	1975	4	
8		1975	4	

B	247	F#	3/2

	Left		Right
f_{av} =	1769	\	1700
c_{av} =	4.0	-	4.0
c_{hw} =	4.0	-	4.0
f_b =	123	/	164
	370	\	329

B	247	E	4/3

I1421d I1419b

Figure 22. Complex Fifths and Fourths: Competing Beat Transitions

Figure 22 displays the first two of four stimulus pairs each of which includes four component partials, all in channel 4. Note the changes in average frequency f_{av} and the beat frequencies f_b. In the tones shown in the upper example, all those potential cues suggest a higher pitch for the right-hand tone, and the subject agreed 100% of the time in the survey. The first time SR2 heard this pair during the anecdotal studies, however, he described the right-hand tone as "lower": on all subsequent hearings he described it as "definitely" higher and on one occasion spontaneously sang an appropriate ascending major second. He volunteered, after several repetitions of this pair, that the [right-hand] tone "beats faster". The term "beats" had not been introduced by the experimenter.

In the lower example of Figure 22 there are conflicting beat frequency cues. The lower frequency beat transition, an increase, seems to have prevailed in 100% of SR2's survey responses. During the anecdotal phase he discovered and volunteered that he could "hear it either way", but denied ever hearing this pair as simultaneously "both" increasing and decreasing in pitch.

Ha	Hb	f_h	Chans	f_b
	4	1481	4	
6		1481	4	
			4	246
7		1728	4	
			4	123
	5	1852	4	

Ha	Hb	f_h	Chans	f_b
	5	1645	4	
			4	82
7		1728	4	
			4	246
	6	1975	4	
8		1975	4	

B 247	F# 3/2	f_{av} =	1687	/	1783	B 247	E 4/3
		c_{av} =	4.0	-	4.0		
		c_{hw} =	4.0	-	4.0		
		f_b =	123	\	82		
			246	-	246		

I1421c I1419c

Ha	Hb	f_h	Chans	f_b
	4	1481	4	
6		1481	4	
			4	370
	5	1852	4	
			4	123
8		1975	4	

Ha	Hb	f_h	Chans	f_b
	5	1645	4	
			4	82
7		1728	4	
			4	246
	6	1975	4	
8		1975	4	

B 247	F# 3/2	f_{av} =	1769	/	1783	B 247	E 4/3
		c_{av} =	4.0	-	4.0		
		c_{hw} =	4.0	-	4.0		
		f_b =	123	\	82		
			370	\	246		

I1421d I1419c

Figure 23. Complex Fifths and Fourths: Learning Effects

Figure 23 contains two more stimulus pairs from the same series. Here we have two cases in which the subject invariably reported the right-hand tone as "lower" in pitch during the statistical survey, and gave an initial anecdotal report that was uncertain but inclined toward "higher". In both cases, after requesting and considering many repetitions of the pairs, SR2 came to a firm percept, immediately reproduced a day and a half later, that "the second sounds like several notes, including some above and below the first".

During our pilot studies, then, we glimpsed two distinct patterns of learning effects in the subject's interpretation of these carefully controlled stimulus pairs based on complex tone intervals (each pattern was observed for several stimuli in addition to the examples given above). In both cases beginning with percepts that were firm and repeatable through 28 single presentations in a variety of contexts within the statistical survey, we observed (1) instances in which repeated listening to a pair led to a recognition of ambiguity in the pitch transition, but ambiguity between two clear and distinct interpretations, and (2) instances in which repeated listening led to a sudden, firm change in percept that then persisted for at least a day and a half with no intervening opportunity to listen to those stimuli. Such possible learning effects are worthy of further investigation.

Also included in our pilot studies were simultaneous complex interval stimuli for 11-channel processors and 6-channel stimuli including more components. Figure 24 provides an example of the latter.

Ha	Hb	f_h	Chans	f_b
	3	1111	3	
			3	123
5		1234	3	
	4	1481	4	
6		1481	4	
			4	370
	5	1852	4	
			4	123
8		1975	4	

Ha	Hb	f_h	Chans	f_b
5		1234	3	
			3	81
	4	1316	3	
6		1481	4	
			4	164
	5	1645	4	
			4	329
	6	1975	4	
8		1975	4	

B	247	
F#	3/2	

f_{av} =	1530	-	1530
c_{av} =	3.7	-	3.7
c_{hw} =	3.6	-	3.6
f_b =	123	\	81
	123	/	164
	370	\	329

B	247
E	4/3

I1421g

I1419d

Figure 24. Complex Fifths and Fourths: More Complicated Stimuli

Here we have six components, three intrachannel beats, and two channels involved in each tone of the pair. Such stimuli offer a sensitive vehicle for investigating competition among multiple potential beat frequency transition cues. The limited data of our pilot studies are consistent with the number of transitions in each direction and the direction and magnitude of the lowest frequency transition both being significant pitch cues. SR2 always reported the right-hand tone in Figure 24 as lower during the survey, but after repeated anecdotal consideration said "[the left tone] is tighter and cleaner [while the other] is on either side of it [in pitch]."

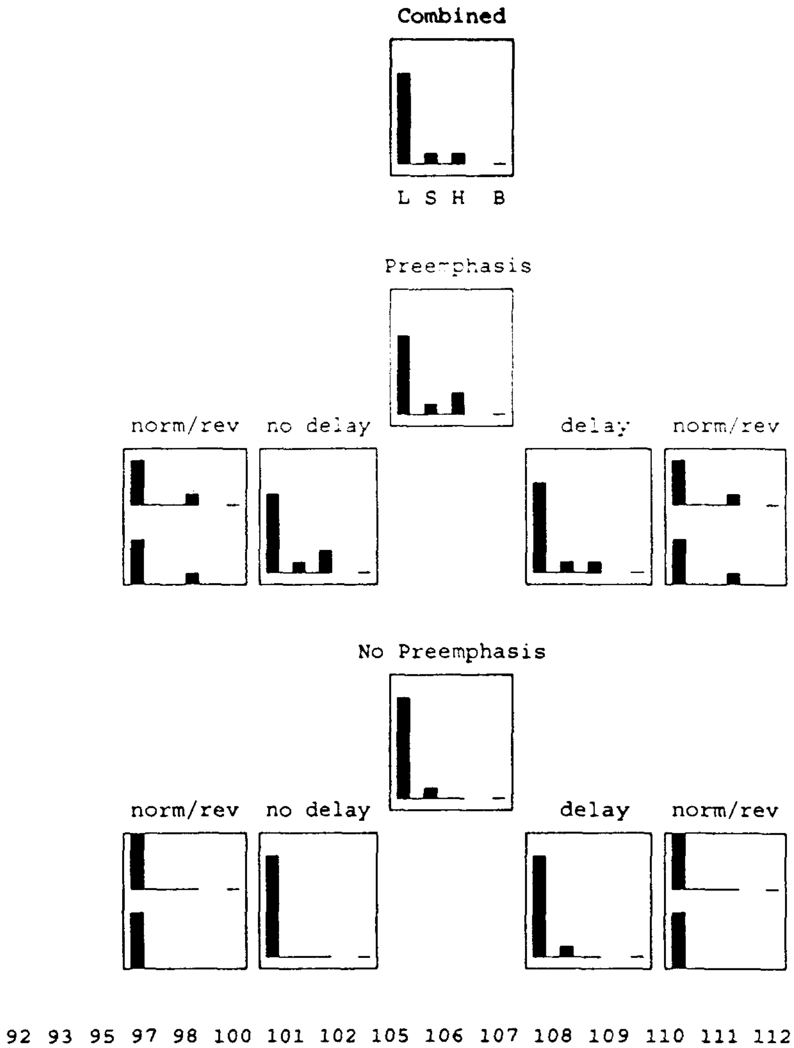


Figure25. Pitch Change Percepts for Descending Beat Frequencies
16 Stimulus Pairs, n = 448

While illustrating some of the intriguing complexity found in our pilot studies we should not neglect the very strong patterns to be found there as well. Figure 25 displays survey results for 16 stimulus pairs based on complex intervals like the examples above. In each of the 16 cases collected in that figure there was a beat frequency transition cue for a *decrease* in pitch (either all or a majority of intrachannel beats showing a decrease). SR2's responses were strongly consistent with the use of that potential cue. [Note that the order of the bars in this figure and the next has been changed to "L S H", so that the left hand bar will contain responses that correspond to the change in (upper) fundamental frequency, as before. This is necessary because of our definition of "normal" order for the complex interval stimuli.]

In Figure 26 we have collected survey results from 6 otherwise similar stimulus pairs containing such a beat frequency transition cue for an *increase* in pitch. Overall there are many

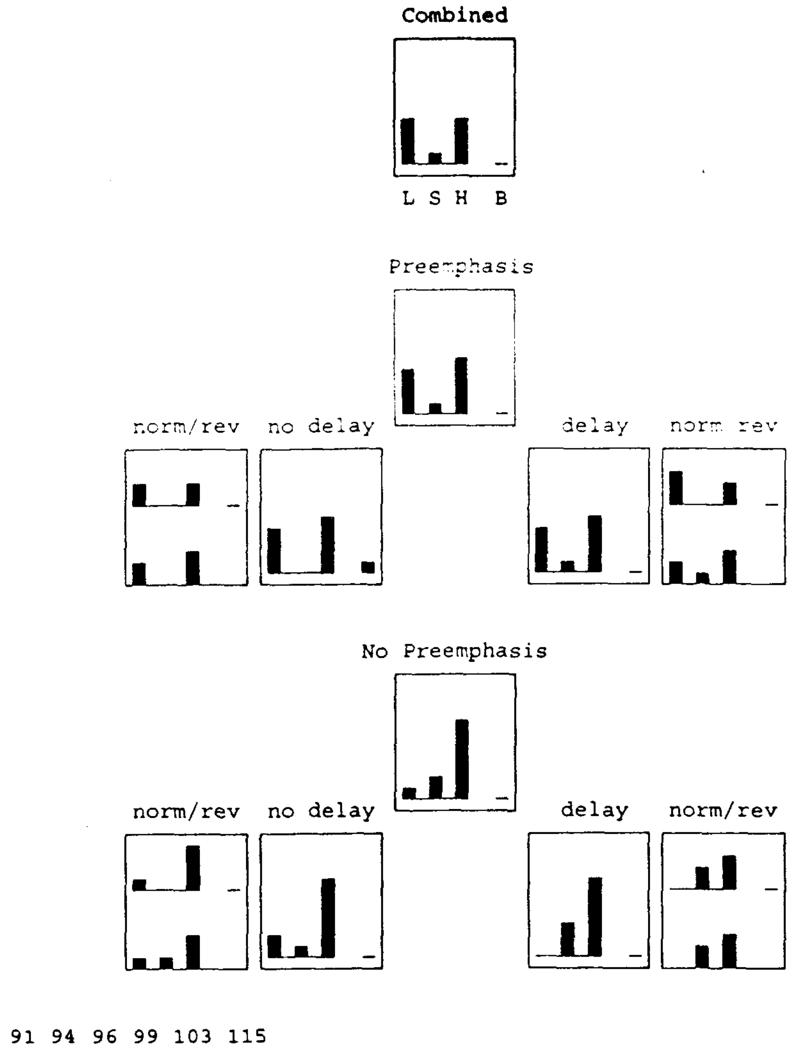


Figure 26. Pitch Change Percepts for Ascending Beat Frequencies
6 Stimulus Pairs, n = 168

more "higher" responses. Where preemphasis filtering was not present, the "higher" response predominated.

Discussion

In our experience, a majority of cochlear implant users find listening to music via their speech processors profoundly disappointing if not unpleasant. This seems especially true for those patients who had the most musical experience and/or training before the loss of normal hearing. (See also Gfeller and Lansing, 1991.)

From time to time however, without any attempt systematically to gather data, we have encountered indications of unsuspected potential for music reception via cochlear implants:

- A patient who had achieved a baccalaureate in music before losing her hearing and receiving a four channel transcutaneous analog device. She volunteered that friends had complimented her on her ability sometimes to sing quite accurately with musical accompaniment. In very brief informal tests, we found her ability to match her voice to a single note's pitch no better than we had suspected. Provided with a musical score, however, and allowed to hear the first several notes in sequence, she continued the melody, singing with surprising pitch accuracy. This observation occurred during the final minutes of this patient's visit to our laboratory, and we have never had an opportunity to conduct further more careful studies with her.
- A patient with a four channel percutaneous device and analog processor, who continues to teach 30 piano lessons per week and takes part in other activities involving music.
- SR2, an avid musician before losing his hearing, cultivated an interest in small ensemble jazz after receiving a four channel percutaneous device and analog processor. He now listens regularly and seriously to musical recordings and performs on several wind and string instruments for his own enjoyment. He has reported that certain CIS processors he has used in the laboratory allow him significantly more access to the subtleties of music. He brings favorite music recordings with which to evaluate new processors during breaks in laboratory speech studies.

As noted at the beginning of this report, our motives in undertaking such a pilot study included hopes (1) of finding better ways of supporting complex tone pitch perception in future processor designs -- for both speech and music reception , (2) of perhaps gaining insights regarding CNS processing of auditory input in general by exploiting stimulus patterns unattainable in normal listeners, and (3) of identifying tools useful in diagnosis and processor optimization for individual implant patients.

We attempted to design a pilot study that would give us useful indications of potential for further study and guidance as to the most productive directions in which to proceed. Given our initial level of ignorance and the very limited amount of patient time available, it was predictable that our pilot studies' results would be patchy and would raise far more questions than they answered. We decided to include conditions (1) with and without a one second delay between compared stimuli, (2) with and without the normal 6 db/octave preemphasis filtering, (3) with both orders of presentation of each stimulus pair, and (4) with both six channel CIS and eleven channel VCIS processors. As shown in this report, each of these distinctions produced significant effects in our pilot data.

Several additional conditions were reluctantly reserved for possible later investigation, including (1) variation of the cutoff frequency and steepness of the envelope smoothing filters on each processor channel, (2) variation of relative phase among constituent harmonics of complex tones, (3) harmonic weightings other than 1/n, (4) loudness balancing of stimuli, (5) use of different channel bandpass filter designs, and (6) use of different envelope amplitude mapping functions in some or all processor channels.

We believe that the results of our pilot studies justify further investigation in several specific directions, some with other cochlear implant users and some with subject SR2. Many of the types of tests included in our pilot study now seem appropriate for more extensive and detailed investigation with several patients, ideally people sharing some pre-deafness musical training and/or experience but differing widely in their experiences listening to music with their clinical devices. Our pilot studies have now established that SR2 is an appropriate subject for a second, more subtle tier of musical perception tests, including identification of complex intervals -- both sequential and simultaneous -- and judgments of timbre, consonance, and dissonance. SR2's ability to make a number of more subtle distinctions could be studied systematically by asking him to identify which among sets of complex trial tones are constituents of more complex reference tones.

Other topics we have noted as deserving of further study include:

- the reintroduction of some harmonics that *don't* meet our specificity criteria to assess their effect on the salience of pitch differences that were reliably detected in these pilot studies.
- patients' ability to match the pitch of their own voices to a presented tone or tone sequence, both when monitoring their own voices with their processors and when unmonitored
- the rare but repeatable exceptions to some of the most consistent patterns within the pilot data
- the intriguing learning effects glimpsed in the course of the pilot studies
- introduction of arbitrary (dissonant) intervals *between* channels while preserving the *within*-channel patterns associated with consistent responses in the pilot studies

We also note that our intrachannel beat technique could be used to support the presentation of relatively low frequency pure tones to any CIS channel in pitch discrimination and other psychophysical studies, using synthesized audio inputs to standard processors.

There appears to be considerable potential for improving cochlear implant patients' access to the music that many of them miss so much, and of improving the speech performance of their devices in the process. Intrachannel beats, for example, might be exploited in processors specifically designed to enhance or preserve them as cues to complex pitch.

References

M. F. Dorman, Abstract for a presentation to an Acoustical Society of America meeting, 1993.

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III. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Initial studies with two subjects implanted with the new Auditory Brainstem Implant.
2. Continued studies of variations of CIS processors -- including the use of adjustable gains and of strategies to mimic the noninstantaneous compression characteristics of cochlear hair cells and the synapses between those cells and primary auditory neurons -- with Ineraid subjects SR2 and SR10.
3. Initial studies with Ineraid subject SR13, to evaluate CIS and VCIS processors.
4. Presentation of project results in invited lectures at the annual meeting of the *American Neurotologic Society* (Minneapolis, MN, October 1, 1993) and at the annual *Neural Prosthesis Workshop* (Bethesda, MD, mid October, 1993).
5. Continued preparation of manuscripts for publication.

Appendix 1

Summary of Reporting Activity for the Period of

May 1 through July 31, 1993

NIH Project N01-DC-2-2401

Reporting activity for the last quarter included publication of one paper and presentations of several invited lectures at the *1993 Conference on Implantable Auditory Prostheses*. Citations are listed below.

Paper

Lawson DT, Wilson BS, Finley CC: New processing strategies for multichannel cochlear prostheses. *Progress in Brain Research* 97: 313-321, 1993.

Presentations

Wilson BS, Lawson DT, Zerbi M, Finley CC: CIS and "virtual channel" CIS (VCIS) processors. Invited lecture presented at the *1993 Conference on Implantable Auditory Prostheses*, Smithfield, RI, July 11-15, 1993.

Lawson DT: Representation of complex tones by CIS processors. Invited lecture presented at the *1993 Conference on Implantable Auditory Prostheses*, Smithfield, RI, July 11-15, 1993.

Finley CC: Factors in electrode design for cochlear implants. Invited lecture presented at the *1993 Conference on Implantable Auditory Prostheses*, Smithfield, RI, July 11-15, 1993. [Principal support for work presented in this lecture was provided by a separate NIH Program Project Grant. Early work to develop electric field models was supported by prior projects with the Neural Prosthesis Program.]

Dorman M: Temporal vs. spatial distinctions with the Ineraid and CIS processors. Invited lecture presented at the *1993 Conference on Implantable Auditory Prostheses*, Smithfield, RI, July 11-15, 1993. [Principal support for work presented in this lecture was provided by a separate NIH Grant. Collaborative efforts by RTI/Duke investigators were supported by the present "speech processors" project with the Neural Prosthesis Program.]