Chapter 5 EXPERIMENTS

5.1 INTRODUCTION

This chapter discuss the experimental procedure that was followed. It mentions the case profiles of the recipients that participated in the study and will focus specifically on electrodograms that show the stimulus pattern and levels of stimulation. The experimental setup of each experiment will be discussed and results will be shown.

5.2 OBJECTIVES

Experiments with the travelling wave encoding strategy aimed to evaluate the potential improvement in pitch discrimination compared to commercial strategies, as perceived by cochlear implant recipients. The hypothesis was that coding sound according to the way described in preceding chapters, should provide a cochlear implant recipient with improved pitch discrimination ability, compared to current, commercial speech coding strategies. Since pitch ranking might be an indicator of speech perception potential (Hanekom & Shannon, 1996), it warrants evaluating the extent to which alternative sound processing strategies (in this case the travelling wave encoding strategy) influence pitch ranking. As discussed in the preceding chapters, the travelling wave encoding strategy seems to convey more information about pure tones than the advanced combination encoder (ACE) strategy and may therefore aid recipients in discriminating smaller pitch differences.

Experiments were designed to assess the pitch discrimination ability of recipients with both a commercial strategy (advanced combination encoder (ACE)) and the travelling wave encoding strategy, applying the hydrodynamic model of the basilar membrane displacement. For this purpose, 21 pure tones around 100 Hz with 1 Hz intervals (90 Hz – 110 Hz) and 21 pure tones around 1 kHz with 10 Hz intervals (0.90 kHz – 1.10 kHz) were pre-processed (signal processing as described Chapter 4) with the Nucleus Matlab Toolbox for stimulation with both advanced combination encoder (ACE) and the travelling wave encoding strategy. These frequency intervals were chosen following visual inspection of the results, as discussed in Chapter 4. If perfect (100%) discrimination was observed, the frequency resolution would have been increased, while too difficult tasks would have resulted in decreased frequency resolution. Frequency resolution at 1 kHz was decreased in anticipation of poorer pitch perception at higher frequencies, as is observed with normal hearing individuals. Prior to assessing the pitch discrimination results, it is important to eliminate other potential differences, such as loudness and duration of the stimuli. The latter is obtained by using identical inputs, leading to stimuli that is the same length.

5.3 EXPERIMENTAL PROCEDURE

The experimental procedure can be divided into three separate procedures, namely loudness balancing, pitch discrimination and pitch ranking. These will be discussed separately.

5.3.1 Loudness balancing procedure

The first part of each experiment was a loudness balancing procedure to ensure that, as far as possible, all the stimuli would be perceived at equal loudness. An adaptive procedure was used to accomplish this. Two stimuli were presented and the recipient had to indicate which of the two sounded louder.

The adaptive procedure is based on a standard zero-seek procedure that approaches the current level at which the test signal will be perceived as equally loud to the reference signal. If the recipient indicated, for example, the reference stimulus to be louder than the test stimulus, the test stimulus' level of stimulation will be increased until the test stimulus is perceived as being louder than the reference stimulus. At this point the direction of the steps will be reversed to decrease the test stimulus loudness. After each reversal, the step size is halved and after the third reversal (in this application) the two sounds were considered to be balanced. Figure 5.1 shows the step size decreases following each reversal. The initial step size was 5% of the tested value, decreasing to 2.5% and 1.25% for the second and third reversal respectively. A typical step size of 1.25% would (for comfort-levels of between 180 and 200 current levels) be two to three current levels. This was accepted as adequate, since the recipients struggled to use smaller step sizes. The centre of the 21 stimuli, for 100 Hz and 1 kHz tone respectively, was selected as the reference with which all the other stimuli were compared. This ensured loudness balancing across all stimuli, i.e. one constant reference against which to compare and adjust all the stimuli.

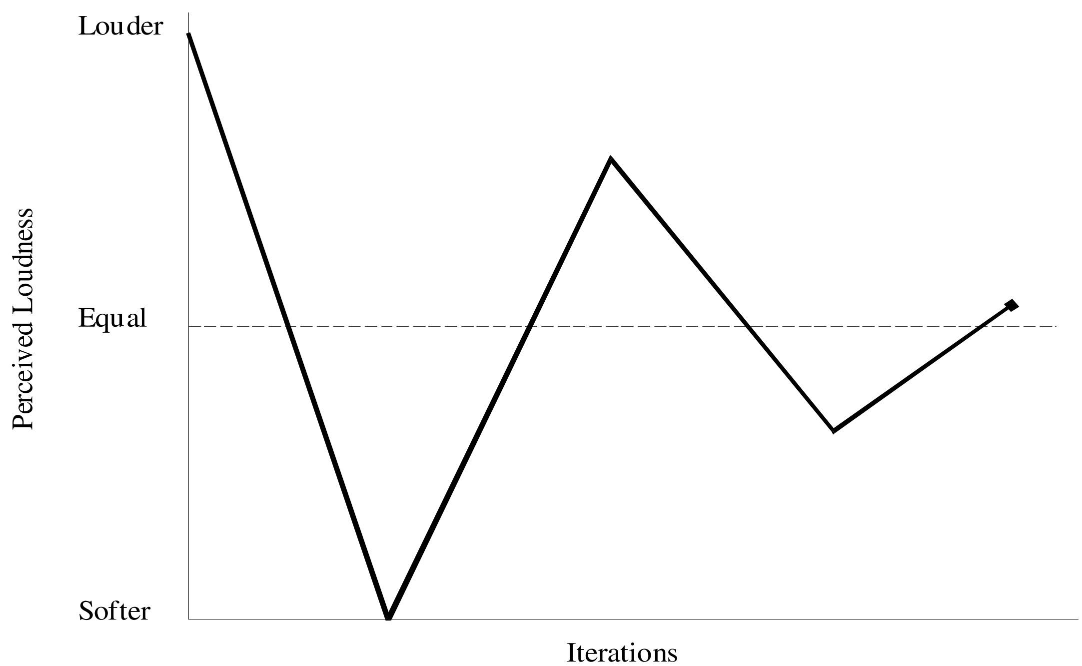

Figure 5.1 Adaptive loudness balancing procedure

5.3.2 Stimulus discrimination experiment

Since the objective is to compare the ability of the travelling wave encoding strategy to convey pitch information to that of commercially available strategies, the stimulus discrimination experiment was conducted as follows. Discrimination was evaluated with a three-interval forced-choice experiment. Three stimuli were presented, with two being the same and one being different. The recipient was asked to identify the 'odd one out'. This experiment did not attempt to connect a perceived pitch to the stimuli, but only to assess if the stimuli could be distinguished from one another.

Each of the 21 sounds was compared to all the others, resulting in 231 comparisons. The compared pairs that were compared with each other were randomly ordered and the 'odd one out' was randomly presented in one of the three intervals. Each recipient completed six repetitions of this experiment for each set of test stimuli. This was deemed to be sufficient, since the patterns that emerged have already stabilised after six repetitions. Only correct answers were counted and normalised to 1 by dividing the number of correct answers by the number of repetitions. A score of 0.0 indicates no discrimination, 0.3 indicates random discrimination and 1.0 represent perfect discrimination. These results can be displayed in a confusion matrix, as shown in Table 5.1. The reference stimuli are represented along the x-axis, while the test stimuli are represented along the y-axis. For example, in row 1 and column 3, sound 1 and 3 were correctly discriminated from each other in three of the six tries (i.e. 0.5). Along the diagonal of this example matrix, each stimulus was compared to itself, preventing any positive discrimination. As the 'distance' between two compared stimuli increases (upward and to the right), the probability of discriminating the two also increases.

Table 5.1 Confusion matrix - example scenario

Stim	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1	1	1	1	1
3	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1	1	1	1
4	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1	1	1
5	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1
7	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1	1
8	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1	1
13	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1	1
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8	1
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	0.8
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.7
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3

If the whole upper triangle approximates a random response, all the stimuli, even the two furthest apart, are impossible to discriminate between and the experiment might need to be adjusted so that presented stimuli are further apart. Conversely, if the only stimuli that are not perfectly identified are the ones where the stimulus is compared to itself, the stimuli may need to be presented at pitches that are closer together.

5.3.3 Pitch ranking experiment

Once the stimulus discrimination experiment is completed, it would be worthwhile to establish whether the different stimuli processed with the travelling wave encoding strategy have tonal qualities that distinguish them or whether another characteristic causes the perceptual difference. A two-interval forced-choice experiment was set up to perform pitch-ranking on all 231 stimuli combinations. A recipient was presented with two stimuli at a time and was asked to choose the one that had the lower pitch. Compared pairs were randomly ordered and the one with a lower frequency was randomly presented in either the first or the second interval. Only correct answers were counted and normalised to by dividing the number of correct answers by the number of repetitions. A score of 0.0 showed 100% certainty on pitch reversal, i.e. the stimulus derived from a higher frequency had a perception of being lower in pitch. A score of 0.5 showed no pitch discrimination, while a score of 1.0 showed 100% certainty of correct pitch, i.e. the stimulus derived from the lower frequency had a perception of being lower in pitch. The results can also be displayed in a matrix form, similar to those of the discrimination experiment. An example of a pitch ranking matrix would look similar to Table 5.1. Stimuli that are far apart would be easy to pitch rank correctly, but as the stimuli become more similar, the score is expected to decrease towards 0.5 – with no difference in tonal quality on the diagonal.

In line with the hypothesis, it is expected that the pitch discriminaiton using the travelling wave encoding strategy would be superior to pitch ranking when using current commercial speech coding strategies. For the same input signals, the confusion matrix obtained with the travelling wave encoding strategy is therefore expected to contain a larger area that is correctly discriminated than one obtained from current commercial strategies.

5.4 BACKGROUND OF RECIPIENTS

The details of the recipients that took part in the experiments are given below. They are part of a group of recipients that regularly assist with experiments at the department.

Table 5.2 Recipient information.

Recipient ID	*S1*	*S9*
Age	*55*	*54*
Etiology	*Progressive loss*	*Progressive loss*
Implanted in tested ear	*6 months*	*3 years*
Implant	*Nucleus 24 Contour Advance*	*Nucleus 24 Contour Advance*
Speech Processor	*ESPrit 3G*	*ESPrit 3G*
Coding strategy	*ACE*	*ACE*
Channel stimulation rate	*900 / 500 Hz*	*900 Hz*
Number of maxima	*10*	*10*

During the experiments, a loaner SPrint speech processor was used, to ensure that no changes could be made to the recipient's own speech processor. Each recipient's details contained in their speech processors were used to obtain threshold and comfort levels (see paragraph 4.3 for an explanation of these levels) necessary for the implementation of the speech coding strategies.

5.5 ELECTRODOGRAMS

Electrodograms are three-dimensional plots, shown in two dimensions, depicting a specific electrode position on the y-axis against time on the x-axis. Each block represents one stimulus pulse, of which the colour depicts the amplitude of stimulation (the third dimension) on the specific electrode at a specific time. When comparing the electrodograms of tones around 100 Hz, processed with the advanced combination encoder (ACE) strategy (see Figures 5.2 and 5.3) almost no change is visible between the two electrodograms in Figures 5.2 and 5.3 even though the stimuli are 10 Hz apart. This was expected since the filter bands at the low frequencies have a maximum resolution of 125

Hz (see Figure 1.4). The only difference between 100 Hz and 90 Hz would be the amplitude of the output of the second filter.

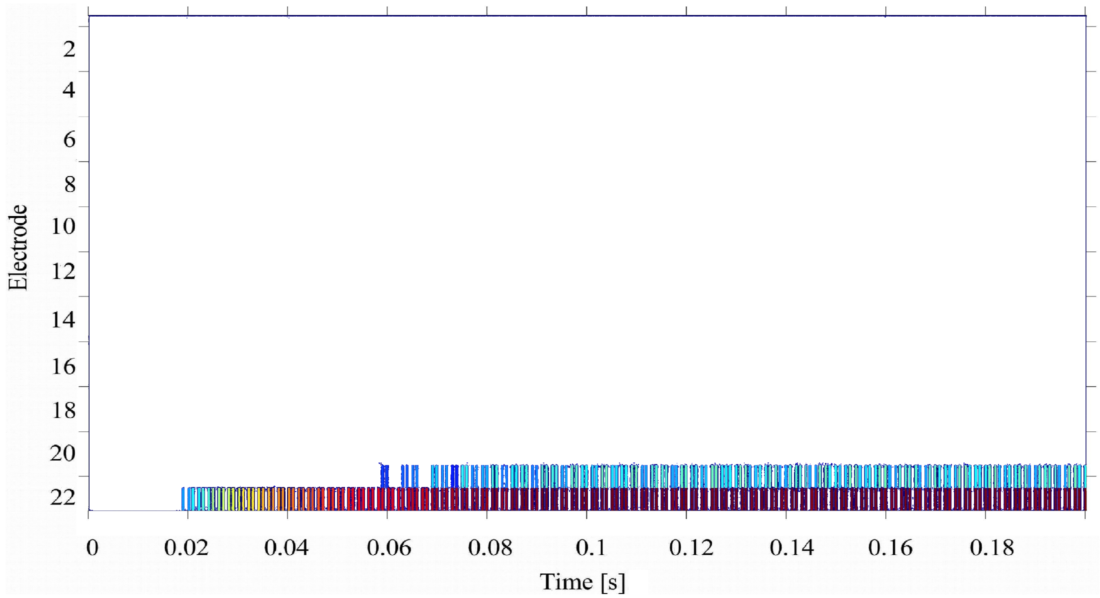

Figure 5.2 Electrodogram of a 90 Hz tone processed with the advanced combination encoder (ACE) speech processing strategy. Two electrodes are activated, with an amplitude difference.

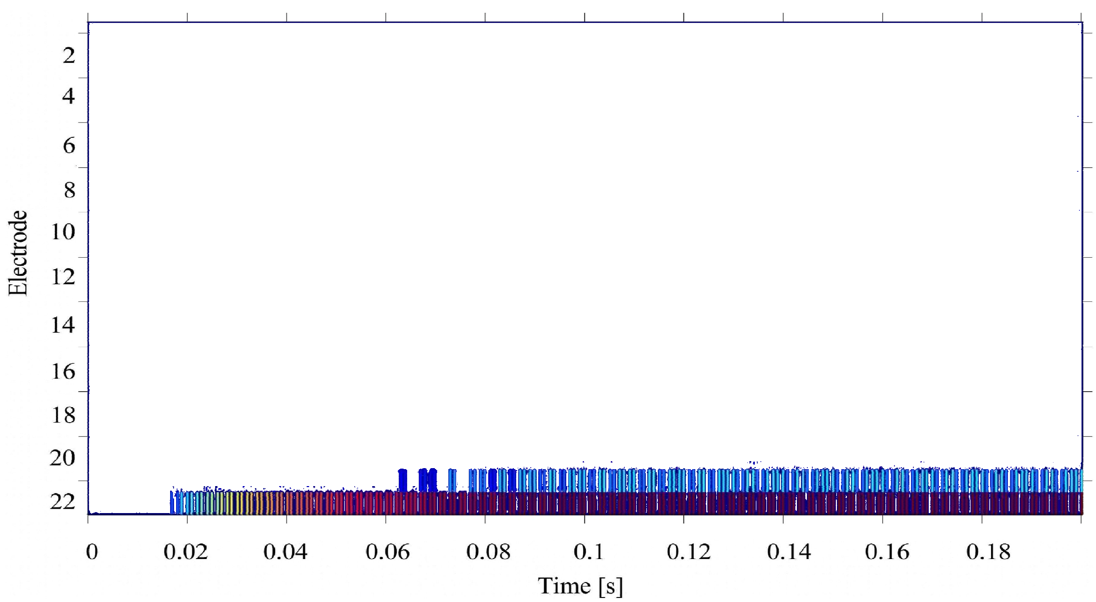

Figure 5.3 Electrodogram of a 100 Hz tone processed with the advanced combination encoder (ACE) speech processing strategy. Virtually identical to the 90 Hz electrodogram.

If the same two tones are processed through the travelling wave encoding strategy, the visual discrimination is much easier (see Figure 5.4 and 5.5). Temporal information (tracking of the 100 Hz tone through the periods of negative basilar membrane deflection) and the spatial information (the progression of the travelling wave towards the point of maximal deflection) allow the stimuli to be distinguished easily. The slowing down of the travelling wave can be seen in Figure 5.4 as a lag of the onset of each burst of stimulation relative to the yellow arrow (straight line for constant velocity) as the travelling wave approaches the apex (electrode 22).

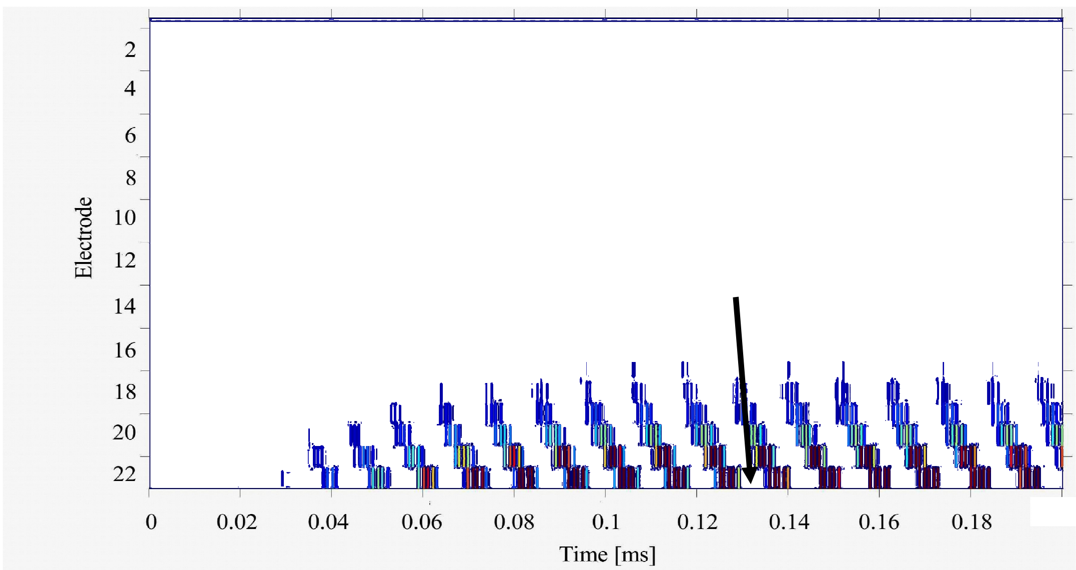

Figure 5.4 Electrodogram of a 90 Hz tone processed with the travelling wave encoding strategy. The travelling wave can be seen moving from the base (low electrode numbers) to the apex (high electrode numbers). The arrow shows constant speed, i.e. the slowing down of the travelling wave can be seen.

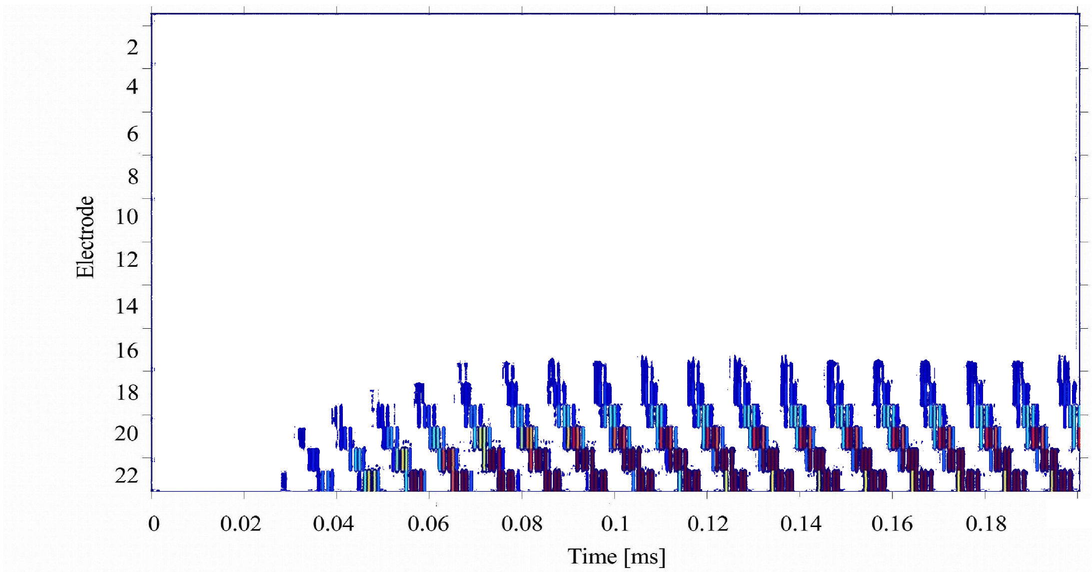

Figure 5.5 Electrodogram of a 100 Hz tone processed with the travelling wave encoding strategy. Visual discrimination between 90 Hz and 100 Hz is possible due to an increased number of activated electrodes and reduced period between pulses, i.e. one extra pulse in 0.1 ms.

The ease with which frequencies close to each other can be visually distinguished from the electrodograms generated by the travelling wave encoding strategy, compared to those generated by advanced combination encoder (ACE), suggests that cochlear implant recipients will also be able to distinguish between these sounds when using the travelling wave encoding strategy.

The sensation of the 100 Hz stimulus should also be perceived as higher pitched when compared to the 90 Hz stimulus due to the increased stimulation on electrodes closer to the base of the cochlea that is normally associated with higher pitch tones (Lesser & Berkley 1971). The recipient should also perceive a tonal quality from the periodic peaks of the travelling wave (McKay & McDermott 1996). The effect that the slowing down of the travelling wave has on pitch percept as it approaches the point of maximal deflection has, as far as is known not been assessed in the literature.

5.6 RESULTS

The results of the three experiments are shown below. The two recipients' results will be reported individually.

5.6.1 Loudness balancing

As can be seen in Figure 5.6, the result of the loudness balancing procedure showed an average change from the initial comfort-level values used ranging from 0.8% to 3.8% across all the processed pure tones and standard deviations ranging from 0.7% to 8.6%.

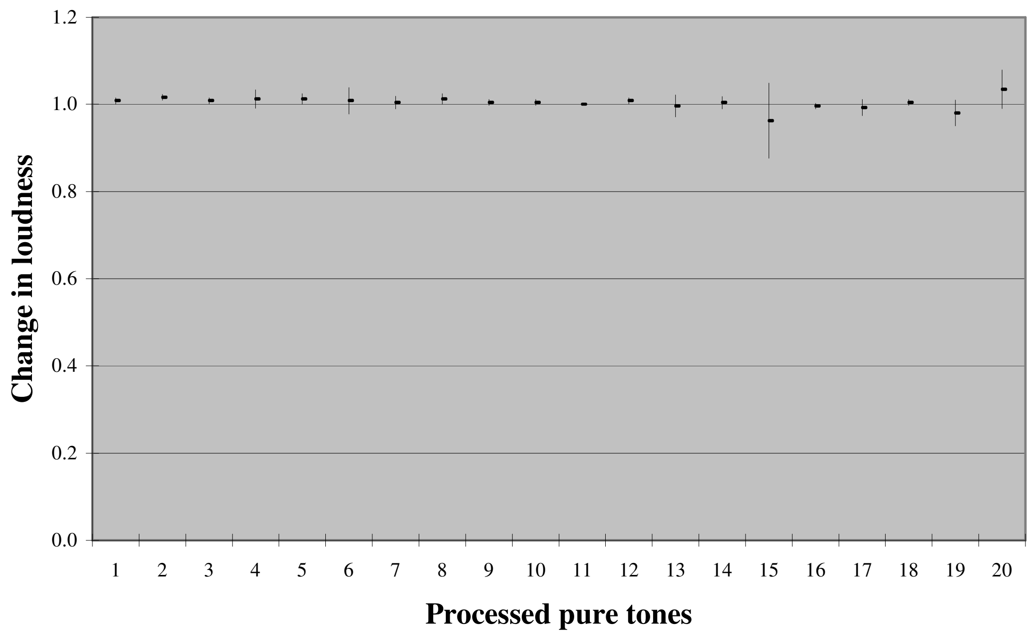

Figure 5.6 An example of loudness balance outcome for S1, showing small deviations from original values. The horizontal axis shows each of the 21 stimuli, derived from 21 different pure tones. The vertical axis shows how the loudness of each stimulus was adjusted in loudness to be perceived as 'equally loud' in comparison to the reference sound (either 100 Hz or 1 kHz – pure tone 11).

The results of the loudness balancing suggests that all the sounds are very similar in loudness and also want to suggest that loudness differences did not influence the discrimination experiments.

5.6.2 Discrimination experiment

The discrimination experiment results are shown in confusion matrices below. In Table 5.3, the discrimination confusion matrix of S1 is shown for the advanced combination encoder (ACE) strategy, after six repetitions of the discrimination experiment were completed. The matrix show the normalised outcome of an experiment with both the columns and rows representing stimuli derived from pure tones, as indicated. Due to the three-interval-forced-choice nature of the experiment, 0.3 indicates random discrimination and 1.0 a constantly correct discrimination. To quantify the data presented in the confusion matrices, a discrimination index D is introduced. D is the mean of each sound's mean discrimination score, i.e. the column and the row for 99 Hz is averaged to obtain the mean discrimination score for 99 Hz with each of the 21 sounds. All 21 sounds' means are averaged to obtain D.

Compared to Tables 5.1 and 5.4 there appears to be no discrimination of stimuli in Table 5.3, D is close to the 0.33 random discrimination level. Even the stimuli furthest apart (stimuli derived from 90 Hz and 110 Hz respectively) could not reliably be distinguished from each other.

Table 5.3 S1 advanced combination encoder (ACE) 100Hz Discrimination Confusion Matrix. D= 0.36 ± 0.04

Hz	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
90	0.3	0.2	0.5	0.3	0.2	0.2	0.5	0.3	0.5	0.5	0	0.5	0.5	0.2	0.3	0.2	0.3	0.2	0.7	0.2	0.5
91	0	0.2	0	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.2	0.3	0.3	0.7	0.3	0.3	0.2	0.5	0.7	0.3
92	0	0	0.3	0.3	0.5	0.2	0.3	0.2	0.7	0.2	0.5	0.3	0.5	0.5	0.3	0.5	0.5	0.2	0.5	0.3	0.2
93	0	0	0	0.5	0.2	0.3	0.5	0.3	0.3	0.3	0.5	0.2	0.7	0.3	0.5	0.5	0.2	0.3	0.5	0.7	0.2
94	0	0	0	0	0.2	0.7	0.5	0.3	0	0.7	0.2	0.3	0.5	0.8	0.2	0.3	0.7	0.3	0.3	0.7	0.2
95	0	0	0	0	0	0.3	0.3	0.2	0.2	0.3	0.5	0.2	0.3	0.5	0.2	0.5	0.5	0.3	0.5	0.5	0.7
96	0	0	0	0	0	0	0.2	0.3	0.2	0.3	0.2	0.5	0.3	0.7	0	0.7	0.2	0.3	0.7	0.3	0.5
97	0	0	0	0	0	0	0	0.2	1	0.3	0.2	0.3	0.5	0.3	0.3	0	0.3	0.7	0.3	0.3	0.2
98	0	0	0	0	0	0	0	0	0	0.3	0.5	0.3	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.5	0
99	0	0	0	0	0	0	0	0	0	0.5	0.3	0.2	0	0.7	0.3	0	0.3	0.3	0.5	0.3	0.2
100	0	0	0	0	0	0	0	0	0	0	0.7	0.5	0.3	0	0.3	0	0	0	0.3	0.3	0
101	0	0	0	0	0	0	0	0	0	0	0	0.2	0.3	0.3	0.2	0.7	0.5	0.3	0.5	0.7	0
102	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0	0.2	0.3	0.7	0.3	0.3	0.2
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.5	0.5	0.3	0.7	0.3	0.7
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7	0.7	0.3	0.3	0.7	0.5
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.3	0.2	0.5	0.3	0.2
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.2	0.2	0.2	0.7
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.5	0.3	0.5
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.7
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3

Table 5.4 shows the higher level of discrimination obtained by S1 (also using six repetitions) with the travelling wave encoding strategy, with D = 0.8 indicating an average of 80% correct discrimination of the pure tones. This equates to an improvement of 40% on discrimination when using the travelling wave encoding strategy. The stimuli used to obtain both the results in Tables 5.3 and 5.4 were computed from identical input signals, as mentioned in Chapter 4.

Table 5.4 S1Travelling wave encoding strategy 100Hz Discrimination Matrix. D= 0.77 ± 0.05

Hz	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
90	0.5	1	0.3	1	1	1	1	1	1	1	1	0.8	1	1	1	0.8	1	1	1	1	1
91	0	0.3	0.3	0.3	0.7	0.7	0.8	0.7	0.7	0.8	1	1	1	1	1	1	1	1	1	1	0.8
92	0	0	0.3	0.5	0.2	0.7	1	0.5	0.8	1	0.8	1	1	1	0.8	1	1	1	1	1	1
93	0	0	0	0.3	0.7	0.8	0.5	0.8	1	0.8	0.8	1	1	1	1	0.8	1	1	1	1	1
94	0	0	0	0	0.5	0.3	0.7	0.3	0.5	0.8	1	1	1	0.7	1	1	1	1	1	1	0.5
95	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	1	0.8	1	1	1	0.8	0.8	1	1	1
96	0	0	0	0	0	0	0.5	0.3	0.5	0.2	0.7	1	1	1	1	1	1	1	0.8	1	0.5
97	0	0	0	0	0	0	0	0.2	0.5	0.5	0.8	0.8	0.8	0.8	1	1	1	1	1	1	0.2
98	0	0	0	0	0	0	0	0	0.5	0.2	0.8	0.8	1	0.8	0.8	1	1	1	1	1	0
99	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	1	1	1	1	0.8	1	1	1	0.8
100	0	0	0	0	0	0	0	0	0	0	0.5	0.8	0.7	0.8	0.7	1	1	0.7	1	0.8	0.8
101	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7	0.7	0.3	0.3	0.8	0.5	0.3	0.8	0.8
102	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.7	0.5	0.8	0.7	0.3	0.5	0.8	0.8
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.3	0.3	0	0.7	0.7	0.5	1
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.2	0.5	0.2	0.3	0.5	1
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.5	0.5	0.2	0.5	1
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.7	0.5	0.5	1
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.3	1
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	1
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3

When compared to Table 5.3, Table 5.5 shows better results obtained from S9 for the same experiment (although only four repetitions were used) when using the advanced combination encoder (ACE) strategy generated stimuli for sounds around 100 Hz, with D = 0.6. Visually, it does not seem to form such a distinct upper-triangle like Table 7.6.

Table 5.5 S9 advanced combination encoder (ACE) 100 Hz Discrimination matrix. D= 0.62 ± 0.06

Hz	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
90	0.8	0.3	0	0.8	1	1	0.3	0.3	0.3	0.5	1	0.8	1	1	0.3	1	0.8	1	0.8	1	1
91	0	0.8	0	0.3	1	0.8	1	0.3	0	0.5	0.5	1	0.8	1	0.8	0.8	0.8	0.5	0.8	0.8	0.8
92	0	0	0.8	0.3	0.8	0.8	0.8	0.5	1	0.5	1	0.8	1	1	0.3	0.3	1	0.5	0.8	0.5	0.5
93	0	0	0	0.5	0.5	0.5	0.5	0.5	0.8	0.8	0.8	1	0.5	0.8	0.8	0.8	0.5	0.5	0.8	0.5	0.3
94	0	0	0	0	0.3	0.5	1	1	0.8	1	0.5	0.5	0.3	0.8	0.8	1	0.8	0.8	0.8	1	0.5
95	0	0	0	0	0	0	0.8	1	0.8	1	0.8	0.5	0.5	0.5	0.8	0.5	0.8	0.5	0.5	0.3	0
96	0	0	0	0	0	0	0.5	0.3	0.8	0.5	1	1	1	0.8	0.8	1	1	1	1	1	1
97	0	0	0	0	0	0	0	0.5	0.8	0.3	1	1	0.5	0.8	0.3	0.8	1	0.3	1	0.3	1
98	0	0	0	0	0	0	0	0	0	0	1	0.5	1	1	0.5	0.3	0.5	0.5	0.8	0.5	1
99	0	0	0	0	0	0	0	0	0	0.8	1	1	0.5	1	0	0.5	0.8	0.5	0.3	0.5	0.8
100	0	0	0	0	0	0	0	0	0	0	0.5	0.3	0.3	0.3	0.5	0.8	0.3	0.5	0.3	0.5	0.5
101	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3	0.3	0.5	0.3	0.8	0.3	0.8	0.3
102	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0.8	1	0.3	0.5	0.8	0	0.3
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1	0.8	0	0.8	1	0.8	0.5
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.5	0.8	0.3	0.8	0.8	1
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.3	0.5	0.8	0.5
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.3	0.5	0.5
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.5	0.8
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.8	0.8
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Like Table 5.4, Table 5.6 also shows a higher level of discrimination when compared to Table 5.5 for S9, with D = 0.7. S9 improved her discrimination by 10% when using the travelling wave encoding strategy and the upper-triangle in the matrix looks more pronounced.

Table 5.6 S9Travelling wave encoding strategy 100 Hz Discrimination Matrix. D= 0.67 ± 0.04

Hz	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
90	0.6	0.1	0.4	0.4	0.6	0.6	0.6	0.7	0.9	1	1	0.7	1	0.7	1	1	1	1	1	1	0.7
91	0	0.1	0.3	0.6	0.1	0.4	0.4	0.6	0.4	0.9	1	0..9	0.9	1	0.9	1	1	1	1	0.7	0.6
92	0	0	0.1	0.4	0.3	0.3	0.4	0.7	0.3	0.7	0.9	1	1	1	1	1	0.9	1	1	0.9	1
93	0	0	0	0.1	0.3	0	0.9	0.7	0.9	0.4	0.7	0.6	1	1	1	1	1	1	1	1	0.9
94	0	0	0	0	0.6	0.3	0.6	0.4	1	1	0.9	0.7	1	1	1	1	1	0.9	0.9	0.7	0.9
95	0	0	0	0	0	0.6	0.3	0.1	0.9	0.7	0.7	0.7	0.9	1	1	1	1	0.9	1	1	1
96	0	0	0	0	0	0	0.3	0.3	0.3	0.6	0.7	0.6	0.9	1	1	0.9	1	0.7	0.9	1	0.9
97	0	0	0	0	0	0	0	0.1	0.1	0.3	0.7	1	1	0.9	1	0.7	0.7	0.9	1	1	1
98	0	0	0	0	0	0	0	0	0.1	0.4	0.1	0.7	1	0.7	0.6	0.7	1	1	0.6	1	0.4
99	0	0	0	0	0	0	0	0	0	0.4	0.6	0.6	0.4	0.7	0.9	1	0.6	0.7	0.9	1	0.3
100	0	0	0	0	0	0	0	0	0	0	0.4	0.6	0.4	0.7	0.7	0.4	0.9	0.7	0.7	0.9	0.4
101	0	0	0	0	0	0	0	0	0	0	0	0.4	0.1	0.1	0.7	0.4	0.7	0.4	1	0.3	0.6
102	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.3	0.4	0.3	0.3	0.3	1	0.4	0.4
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.9	0.1	0.4	0.7	0.4	0.7	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.6	0	0.4	0.6	0.6	0.7
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.1	0.4	0.3	0.9
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.1	0.4	0.7	0.6
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0.6	0.9
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.7
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Discrimination for the higher frequency pure tones were almost identical for S1 when comparing the advance combination encoder (ACE) strategy and the travelling wave encoding strategy (see Table 5.7 and Table 5.8), with D = 0.8 in both instances. Both experiments used six repetitions. The discrimination compares well with the discrimination at 100 Hz for S1, although the frequency steps are 10 Hz apart. The travelling wave encoding strategy does not seem to improve discrimination for S1 at frequencies around 1 kHz.

Table 5.7 S1 advanced combination encoder (ACE) 1 kHz Discrimination matrix. D= 0.77 ± 0.05

kHz	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
0.90	0.3	0.7	0.5	0.7	0.3	0.5	0.5	1	1	0.8	1	1	1	1	0.8	1	1	1	1	1	0.8
0.91	0	0.5	0.3	0.5	0.7	0.2	0.7	0.7	0.5	0.8	1	0.8	1	1	1	1	1	1	1	1	0.8
0.92	0	0	0	0.7	0.2	0.5	0.7	0.7	0.8	1	1	1	1	1	0.8	1	1	1	1	1	1
0.93	0	0	0	0.5	0.3	0.7	0.7	0.7	0.7	0.8	1	0.7	0.8	1	1	1	1	1	1	1	0.7
0.94	0	0	0	0	0.3	0.5	0.2	0.7	0.3	0.8	1	1	1	1	1	1	1	0.8	0.8	1	1
0.95	0	0	0	0	0	0.3	0.5	0.5	0.7	0.7	0.8	1	0.8	0.8	1	1	1	1	1	0.8	0.7
0.96	0	0	0	0	0	0	0.5	0.3	0.3	0.7	0.5	0.7	1	1	1	1	1	1	0.8	1	0.2
0.97	0	0	0	0	0	0	0	0	0.5	0.3	0.8	1	1	1	1	0.8	1	1	1	1	0.5
0.98	0	0	0	0	0	0	0	0	0	0.8	0.5	1	1	1	1	1	1	1	1	0.8	0.2
0.99	0	0	0	0	0	0	0	0	0	0	0.5	0.8	0.7	0.8	0.8	1	1	1	1	1	0.7
1.00	0	0	0	0	0	0	0	0	0	0	0.7	0	0.8	0.7	0.7	0.8	1	1	1	1	0.2
1.01	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.2	0.7	0.7	1	1	1	1	0.7
1.02	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.8	0.5	0.7	0.8	1	1	1	1
1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.7	0.7	0.8	0.8	1	0.8
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.2	0.5	0.8	0.7	0.8	1
1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.7	0.7	1
1.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.7	0.2	0.3	0.8
1.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.5	0.5	1
1.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.3	0.8
1.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1
1.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5

Table 5.8 S1Travelling wave encoding strategy 1 kHz Discrimination matrix. D= 0.80 ± 0.08

kHz	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
0.90	0.2	1	0.5	1	1	1	0.8	1	1	0.8	1	1	1	1	1	1	1	1	1	1	1
0.91	0	0.2	0.7	0.8	0.8	0.8	0.8	0.8	1	0.8	1	1	1	1	1	1	0.8	1	1	1	1
0.92	0	0	0.2	0.8	0.5	0.2	1	0.5	1	1	0.8	0.8	0.7	1	1	1	0.8	1	1	1	1
0.93	0	0	0	0.2	0.5	0.2	0.3	0.7	1	0.5	0.8	0.7	0.8	1	0.8	1	1	1	1	1	0.5
0.94	0	0	0	0	0.2	0.2	0.5	0.5	1	0.7	0.2	0.7	0.8	1	1	0.8	1	1	0.8	0.8	0.7
0.95	0	0	0	0	0	0.2	0.3	0.3	1	0.5	0.7	0.5	0.7	0.8	1	1	0.8	1	1	1	0.8
0.96	0	0	0	0	0	0	0.2	0.2	1	0	0.5	1	0.3	1	1	1	0.8	0.8	0.8	1	0.7
0.97	0	0	0	0	0	0	0	0.5	0.8	0.8	0.3	0.7	0.7	1	1	0.7	0.8	1	1	1	0.3
0.98	0	0	0	0	0	0	0	0	0.2	1	0.8	0.7	1	1	1	1	1	1	1	1	0.8
0.99	0	0	0	0	0	0	0	0	0	0.5	0.5	0.7	0.8	1	1	0.7	1	1	1	1	0.8
1.00	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.7	1	0.8	1	0.8	0.8	1	1	0.7
1.01	0	0	0	0	0	0	0	0	0	0	0	0.8	0.8	0.8	1	0.7	0.7	1	1	1	0.7
1.02	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	0.7	0.8	0.5	0.7	1	0.7	0.3
1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.8	1	0.8	1	1	0.8
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.2	0.7	0.8	1	0.8
1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7	0.5	0.8	1	0.8
1.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	1	0.8	1
1.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.5	0.8	1
1.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.8	0.8
1.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Comparing Table 5.9 and Table 5.10, the travelling wave encoding strategy seems to give worse discrimination for S9 with D = 0.4 when compared to the advance combination encoder (ACE) strategy, with D = 0.8 (Although only three repetitions were obtained for Table 5.9 and six for Table 5.10) The discrimination score for Table 5.10 approaches the 0.33 random-score.

Table 5.9 S9 advance combination encoder (ACE) 1 kHz Discrimination matrix. D= 0.76 ± 0.05

kHz	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
0.90	0.3	0.7	0	0	0	0.3	0.7	1	1	1	1	1	1	1	0.7	0.7	1	1	1	1	1
0.91	0	0.7	0	0.7	0.7	0.7	0.3	1	1	1	1	1	1	1	1	1	1	1	1	1	0.7
0.92	0	0	0.7	0	0.3	1	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.93	0	0	0	0.3	0.3	0.3	0.7	0.7	1	1	1	1	1	1	1	1	1	1	1	1	1
0.94	0	0	0	0	0.3	0.3	1	1	1	1	1	1	1	0.7	1	1	1	1	1	1	1
0.95	0	0	0	0	0	0	0.7	0.3	1	1	1	1	1	1	0.7	1	1	1	1	1	1
0.96	0	0	0	0	0	0	0.3	0	0.3	0.7	1	1	0.7	1	1	1	1	1	1	1	0.7
0.97	0	0	0	0	0	0	0	0.3	0.3	0.7	0.7	0.7	0.7	1	1	1	1	0.7	1	1	0.7
0.98	0	0	0	0	0	0	0	0	0.3	0	0.3	0.7	0	0	0.7	1	1	1	1	1	0
0.99	0	0	0	0	0	0	0	0	0	0.3	0	0.7	0.7	0.7	1	1	1	0.7	1	1	0.3
1.00	0	0	0	0	0	0	0	0	0	0	0.3	0	0.7	0.3	0.7	1	1	1	0.7	1	0.7
1.01	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.3	0.7	1	1	1	1	1	0.3
1.02	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0.7	0.7	0.7	1	1	1	0.3
1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.7	0.7	1	0.7	1	1
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	1	0.3	0.3	1
1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.7	0.7	0.7
1.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.7	0.3	1
1.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.3	1
1.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.3
1.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 5.10 S9 Travelling wave encoding strategy 1 kHz Discrimination matrix. D= 0.42 ± 0.05

kHz	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
0.90	0.3	0.6	0.9	0.6	0.3	0.3	0.3	0.6	0.4	0.6	0.4	0.6	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4
0.91	0	0.6	0.4	0.4	0.6	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.3	0.4
0.92	0	0	0.4	0.4	0.4	0.3	0.3	0.6	0.1	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.3	0.1
0.93	0	0	0	0.3	0.6	0.6	0.3	0.1	0.7	0.9	0.4	0.1	0.3	0.3	0.3	0.3	0.6	0.4	0.3	0.3	0.3
0.94	0	0	0	0	0.3	0.1	0.6	0.7	0.6	0.3	0.4	0.3	0.1	0.6	0.3	0.1	0.4	0.4	0.4	0.4	0.6
0.95	0	0	0	0	0	0.6	0.7	0.9	0.4	0.9	0.7	0.9	0.3	0.6	0.1	0	0.4	0.4	0.4	0.4	0.6
0.96	0	0	0	0	0	0	0.4	0.7	0.7	0.9	0.1	0.3	0.4	0.6	0.3	0.1	0.3	0.3	0.4	0.4	0.6
0.97	0	0	0	0	0	0	0	0.6	0.4	0.4	0.1	0.4	0.3	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.6
0.98	0	0	0	0	0	0	0	0	0.6	0.4	0.1	0.6	0.3	0.4	0.3	0.3	0.3	0.4	0.4	0.4	0.3
0.99	0	0	0	0	0	0	0	0	0	0.3	0.6	0.3	0.4	0.4	0.4	0.4	0.1	0.6	0.3	0.3	0.1
1.00	0	0	0	0	0	0	0	0	0	0	0	0.6	0.4	0.6	0.3	0.4	0.3	0.3	0.4	0.4	0.7
1.01	0	0	0	0	0	0	0	0	0	0	0	0.7	0.4	0.6	0.4	0.3	0.1	0.4	0.4	0.4	0.4
1.02	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.9	0.4	0.4	0.4	0.4	0.3	0.4	0.7
1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0.6	0.3	0.4	0.4	0.4	0.9
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.3	0.1	0.4	0.4	0.4	0.7
1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0.4	0.1	0.4	0.9
1.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.4	0.3	0.4	0.9
1.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.1	0.4	1
1.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.4	0.9
1.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.9
1.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3

Comparing the results from the 100 Hz stimuli with the results from the 1 kHz stimuli it can be noted that the travelling wave encoding strategy seems to give improved discrimination over the advanced combination encoder (ACE) strategy when processing low frequency sounds for both S1 and S9, with a more pronounced benefit seen in S1. S1 showed an improvement from D = 0.4 to D = 0.8 and S9 showed an improvement from D = 0.6 to D = 0.7.

When higher frequency sounds are processed the travelling wave encoding strategy seems to give equal or worse discrimination ability to the recipient when compared to the advanced combination encoder (ACE) strategy. S1 obtained D = 0.8 using both strategies and S9 obtained D = 0.8 using advanced combination encoder (ACE) and D = 0.4 when using travelling wave encoding strategy. These results are summarised in Table 5.11.

Table 5.11 Discrimination indices for both 100 Hz and 1 kHz for S1 and S9 using six repetitions of 231 comparisons.

Frequency of stimuli	Recipient	D for advanced combination encoder (ACE)	D for travelling wave encoding
100 Hz	S1	0.36 ± 0.04	0.77 ± 0.05
	S9	0.62 ± 0.06 *	0.67 ± 0.04
1 kHz	S1	0.77 ± 0.05	0.80 ± 0.08
	S9	0.76 ± 0.05 **	0.42 ± 0.05

* Only four repetitions used

** Only three repetitions used

With a sample size of two recipients, proper statistical analysis could not be done on the experimental data, although some trends was noticed. The travelling wave encoding strategy seems to improve the discrimination of 21; 1 Hz separated pure tones around 100 Hz to about 80% correct on average across all 21 sounds with about 10% variance across the sounds. This suggests that there are some additional information included in the travelling wave encoding strategy that allows users to discriminate pure tones around 100 Hz more accurately.

The travelling wave encoding strategy does not seem to improve discrimination of pure tones around 1 kHz (or might even decrease discrimination, as with S9). This suggests that the additional information presented to the recipient for pure tones around 100 Hz is lost at the higher frequency of 1 kHz. These results will be further discussed in Chapter 6.

5.6.3 Pitch ranking experiment

Stimuli presented for pitch ranking experiments were processed only with the travelling wave encoding strategy, since the nature of stimulation is different from current strategies and the improved discrimination shown in Table 5.4 and Table 5.6 (when compared to Tables 5.3 and 5.5) does not necessarily carry pitch information. Since the advanced combination encoder (ACE) strategy rely on the tonotopicity of the cochlea alone and good pitch ranking shown in literature (Hanekom & Shannon 1996), pitch ranking experiments was not conducted with the advance combination encoder (ACE) strategy.

The pitch ranking experiments were also reported in Tables, similar to the discrimination experiments, with values as discussed in paragraph 5.3.2. D is computed in the same way as for the discrimination experiments (see paragraph 5.6.2) and indicates the accuracy with which the recipient can rank the pitch of the various sounds. The results of the pitch ranking experiment, using the 100 Hz stimuli, are shown in Tables 5.11 and 5.12 for S1 and S9 respectively. Both shows good pitch ranking with D = 0.8 or 80 % correct pitch ranking.

The pitch ranking ability looks similar to the discrimination found in Tables 5.4 and 5.6 (i.e. the sounds that was correctly discriminated was also correctly pitch-ranked) and indicates that both recipients could correctly pitch-rank different stimuli when pure tones processed with the travelling wave encoding strategy differed by 2 – 3 Hz. An interesting exception is the repeatable pitch reversal (values below 0.5) that was found when comparing 110 Hz with tones from 101 Hz to 109 Hz in both recipients.

Table 5.12 S1Travelling wave encoding strategy 100 Hz Pitch Ranking matrix. D= 0.78 ± 0.08

Hz	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
90	0.2	0.5	0.5	0.8	0.7	0.8	1	1	0.7	1	1	1	1	1	1	1	1	1	1	1	1
91	0	0.5	0.5	0.5	0.3	0.8	0.8	0.7	1	1	0.8	1	1	1	1	1	1	1	1	1	1
92	0	0	0	0.2	0.5	0.3	0.7	0.8	0.7	1	1	0.8	1	1	1	1	1	1	1	1	1
93	0	0	0	0.5	0.5	0.7	0.7	0.5	1	0.7	1	1	1	1	1	1	1	1	1	1	1
94	0	0	0	0	0.7	0.5	0.8	0.5	0.3	0.8	1	1	1	1	1	1	1	0.8	1	1	0.8
95	0	0	0	0	0	0.3	0.8	0.8	0.5	0.8	0.7	0.8	1	1	1	0.8	1	1	1	1	0.7
96	0	0	0	0	0	0	0.5	0.7	0.7	0.7	0.7	1	1	1	1	1	1	1	1	1	0.8
97	0	0	0	0	0	0	0	0.5	0.8	0.7	0.8	0.8	1	1	1	1	1	1	1	1	1
98	0	0	0	0	0	0	0	0	0.5	0.7	0.8	0.7	0.8	1	1	1	1	0.8	1	1	0.5
99	0	0	0	0	0	0	0	0	0	0.8	0.7	0.7	1	0.8	1	1	1	1	1	1	1
100	0	0	0	0	0	0	0	0	0	0	0.2	0.8	1	1	0.8	1	0.8	1	0.7	0.8	0.7
101	0	0	0	0	0	0	0	0	0	0	0	0.3	0.2	0.8	0.5	1	0.7	0.7	0.8	0.5	0
102	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.3	0.7	0.5	0.8	0.7	0.8	0.2
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0.3	0.7	0.8	0.7	0.5	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.7	0.8	0.7	0.3	0
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.8	0.3	0.7	0.3	0
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.5	0.3	0.8	0
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.7	0.3	0.2
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.3	0.2
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7

Table 5.13 S9 Travelling wave encoding strategy 100 Hz Pitch Ranking matrix. D= 0.78 ± 0.07

Hz	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110
90	0.3	0.4	0.9	0.7	0.4	0.4	0.6	0.9	1	0.7	1	1	1	0.9	1	0.9	1	1	1	0.9	1
91	0	0.4	0.9	0.6	0.6	0.9	1	0.4	0.7	1	1	1	1	0.9	1	1	1	1	1	1	1
92	0	0	0.7	0.3	0.4	0.4	0.9	0.4	0.4	1	1	1	1	1	0.9	0.9	1	1	1	1	0.9
93	0	0	0	0.7	0.6	0.7	0.7	0.9	0.7	0.9	0.6	1	1	1	1	1	1	1	1	1	1
94	0	0	0	0	0.3	0.6	0.3	0.7	1	0.9	1	0.9	1	1	1	1	1	0.7	0.9	1	1
95	0	0	0	0	0	0.4	0.6	0.9	0.6	0.9	0.9	1	1	1	1	0.9	1	1	1	1	1
96	0	0	0	0	0	0	0.6	0.6	0.9	1	1	0.9	0.7	1	1	0.9	1	0.9	1	1	0.9
97	0	0	0	0	0	0	0	0.3	0.9	0.7	0.9	1	0.9	1	0.9	1	0.9	1	1	1	1
98	0	0	0	0	0	0	0	0	0.7	0.9	0.7	0.7	1	1	1	1	1	1	1	0.9	0.7
99	0	0	0	0	0	0	0	0	0	0.3	0.3	0.6	0.9	0.6	0.9	1	0.9	1	0.9	1	0.6
100	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0.7	0.9	1	0.9	0.7	1	1	1	0.6
101	0	0	0	0	0	0	0	0	0	0	0	0.3	0.7	0.7	0.7	1	1	0.9	0.9	1	0.1
102	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7	0.7	0.9	0.9	0.3	1	0.9	0
103	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.4	0.6	0.9	0.9	0.7	0.4	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.3	0.6	0.4	0.9	0.9	0.3
105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.1	0.6	0.6	0.7	0
106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.6	0.1	0.7	0.1
107	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.6	0.3	0.6	0
108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4	0.9	0
109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4

The stimuli generated from pure tones in the range around 1 kHz were also used during pitch ranking experiments. Results are displayed in Tables 5.13 and 5.14. These results indicate poor pitch quality of stimuli with many pitch reversals (D = 0.4 and 0.2 for S1 and S9 respectively) and frequent inability to do pitch ranking when using the travelling wave encoding strategy.

Table 5.14 S1 Travelling wave encoding strategy 1 kHz Pitch Ranking matrix. D= 0.37 ± 0.15

kHz	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
0.90	0.5	1	0.5	1	1	1	1	0.5	1	0.5	0.5	1	0.5	1	1	0	0.5	0	0	0	0.5
0.91	0	0.5	0.5	0	0.5	0	0	0	0.5	0	0	0.5	0	1	0	0	0	0	0	0	0
0.92	0	0	0.5	1	0	0	0	0	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0.5
0.93	0	0	0	1	0.5	0.5	0.5	0.5	0.5	0	0.5	0	0	0.5	0.5	0	0	0.5	0	0	1
0.94	0	0	0	0	0.5	0	0.5	0	1	1	0.5	1	0	0.5	1	0	0	0.5	0	0	0
0.95	0	0	0	0	0	0.5	0	0.5	1	0	0.5	1	0	0.5	1	0	0	0.5	0	0	0.5
0.96	0	0	0	0	0	0	0.5	0.5	1	0.5	0.5	0.5	0.5	1	0.5	1	0	0	0	0	1
0.97	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	0.5	0.5	0	0	0	0.5
0.98	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0.5	0	0	0	0	0	0
0.99	0	0	0	0	0	0	0	0	0	1	0.5	1	0	1	1	0	0.5	0	0	0	1
1.00	0	0	0	0	0	0	0	0	0	0	1	1	0.5	1	0	0.5	0	0	0	0	0.5
1.01	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0.5	1	0	0	0	0	0
1.02	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	1	1	0.5	0	0	0	1
1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0.5	0	0	0.5
1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1	0	0	0	1
1.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	1
1.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.5	0	1
1.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	1
1.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5

Table 5.15 S9 Travelling wave encoding strategy 1 kHz Pitch Ranking matrix. D= 0.21 ± 0.11

kHz	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
0.90	0.5	0.2	0.8	0.7	0	0	0	0.3	0	0.3	0	0.2	0	0	0	0	0	0	0	0	0
0.91	0	0.8	0.3	0	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.92	0	0	0.8	0.2	0	0	0	0.3	0	0.2	0	0	0	0	0	0	0	0	0	0	0
0.93	0	0	0	0.2	0.5	0.3	0.3	0.7	0.5	1	0	0	0	0	0.3	0	0.2	0	0	0	0.2
0.94	0	0	0	0	0.5	0	0.8	0.8	0.3	0.7	0.5	0	0	0.7	0	0.3	0	0	0	0	0.2
0.95	0	0	0	0	0	0.7	0.7	1	0.5	0.7	0.7	1	0	0.5	0	0	0	0	0	0	0.5
0.96	0	0	0	0	0	0	0.5	1	1	1	0	0.2	0	0.3	0	0	0	0	0	0	0.3
0.97	0	0	0	0	0	0	0	0.8	0.5	0.8	0	0.3	0	0	0	0	0	0	0.3	0	0.5
0.98	0	0	0	0	0	0	0	0	0.7	0.3	0	0.2	0	0	0	0	0	0	0	0	0
0.99	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0.5
1.00	0	0	0	0	0	0	0	0	0	0	0.3	0.5	0.3	0.3	0	0	0	0	0	0	0.7
1.01	0	0	0	0	0	0	0	0	0	0	0	1	0.2	0.8	0	0.3	0	0	0	0	0.7
1.02	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.7	0	0.2	0.3	0	0	0	1
1.03	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0.5	0	0	0	0	1
1.04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0.3	0	0	0	0	1
1.05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.8	0	0	0	1
1.06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.3	0.2	0	1
1.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0	1
1.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0.3	1
1.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	1
1.10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The pitch ranking experiments seems to correlate with the suggestion made at the end of paragraph 5.6.2, namely that the pure tones around 100 Hz, when processed with the travelling wave encoding strategy seems to carry additional (pitch) information that assist recipients when trying to discriminate pure tones. Pure tones around 1 kHz, when processed through the travelling wave encoding strategy does not seem to carry pitch information (D = 0.4 and 0.2) and does not improve the discrimination of recipients when listening to these sounds.

5.7 SUMMARY

This chapter discussed the experimental procedure that was followed. It also focussed specifically on electrodograms that show the stimulus pattern and levels of stimulation. The experimental setup of each experiment was discussed and tabled results were shown. The travelling wave encoding strategy enabled the two recipients to discriminate and correctly pitch-rank stimuli derived from pure tone differing by 2 – 3 Hz (or 80% across 21 sounds), centred around 100 Hz. The travelling wave encoding strategy did not enable recipients to discriminate better at frequencies centred around 1 kHz.