5 Results

5.1 Introduction

Many studies succeeded to find a correlation between distortion product otoacoustic emissions and pure tone thresholds (Durrant, 1992, Avan & Bonfils, 1993; Gaskill & Brown, 1990). Other researchers attempted to predict hearing status in normal hearing and hearing-impaired populations as being normal or impaired with DPOAEs (Gorga et al., 1993; Kimberley et al., 1994; Moulin et al., 1994). To the author's knowledge, there has not been a report of the prediction of specific decibel values for pure tone thresholds for normal hearing and hearing-impaired subjects with DPOAEs to date. All studies attempting to predict hearing ability with DPOAEs classified hearing as being normal or abnormal but once a hearing loss was identified, no attempts were made to speculate what the exact degree of hearing loss was at that frequency. This study attempted to predict the pure tone thresholds of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz within 10dB categories of hearing loss.

Scenario three was the first scenario where the neural network was able to predict hearing ability for normal and hearing impaired ears. This was partly due to the fact that the presentation of input data to the neural network was in a new binary format, allowing the network to use present and absent responses as input data.

5.2 Scenario Three: Prediction of Average Hearing Ability

For scenario three, every audiogram was graded into seven categories of average hearing ability. Each category spanned 10 dB, category one ranged from 0-10dB, category two from 11-20 dB, three from 21-30 dB and so forth. The seven categories can be seen in Table IV. Each category of hearing ability was determined by taking the average of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. Each ear had one number in the end, depicting its average hearing ability according to one of the seven categories. The neural network had to predict this average hearing ability.

Before the actual results of the prediction are given, it is deemed necessary to comment on the first two categories depicting the normal range of hearing. Description of hearing impairment is based on definitions of "normal hearing" that have been recommended in the medical profession. The American Academy of Otolaryngology and the American Council of Otolaryngology (AAO-ACO) recommended in 1979 that impaired hearing function begin at an average hearing level of 25dB HL (cited in Yantis, 1994). Goodman (1965) (cited in Yantis, 1994) also recommended normal hearing to include hearing ability up to 25dB HL but Clark (1981) (cited in Yantis, 1994) recommended normal hearing from –10dB to 15dB. In this study, the first category spans 0-10dB and the second 11-20dB. For this study, it was decided to describe results that were in the first two categories (0-20dB) as an indication of normal hearing. The first category (0-10dB) is sometimes referred to as very good hearing ability at a specific frequency. Other researchers have also used 0-20dB as the criteria for normal hearing (Probst & Hauser, 1990; Stover et al, 1996a).

5.2.1 The Prediction of Average Hearing Ability in the Seven 10dB Categories

The results of the neural network's prediction of average hearing ability is discussed below.

The overall prediction of the neural network across all seven categories were completely accurate (predicted in the same category as the actual hearing average) 40% of the time. The network predicted average hearing ability as being in an adjacent 10dB class 30% of the time. The network predicted average hearing ability as completely wrong 30% of the time. This overall prediction ability of the neural network does not seem to be very good, but when the prediction of some of the categories is investigated separately, the picture changes considerably. The neural network was able to predict very good average hearing ability (0-10dB) correctly 91% of the time. In this first category (0-10dB), the network predicted average hearing as being in the adjacent 10dB class (11-20dB) 9% of the time. Very good average hearing (0-10dB) were therefore predicted as "normal" (0-20dB) 100% of the time. The results for all the categories are presented in Table VII.

Table VII: Results of the neural network's prediction accuracy for average hearing ability for the seven 10dB categories.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
100% correct	91%	11%	23%	0%	27%	25%	0%
one class out	9%	58%	54%	31%	20%	31%	100%
completely wrong	0%	31%	23%	69%	53%	44%	0%
0-10dB predicted as <20dB	100%	-	-	-	-	-	-
0-20dB predicted as 0-20dB	87%	-	-	-	-	-	-

One aspect that should be kept in mind is the sensitivity and specificity of any procedure that might potentially be used as a hearing screening or diagnostic procedure. The sensitivity of a test refers to the test's ability to correctly identify subjects with a hearing loss whereas the specificity refers to the test's ability to correctly identify normal hearing (Konkle & Jacobson, 1991). Sensitivity and specificity is tied directly with the predictive value of a test. The more sensitive a test, the better it's negative predictive value, and the more specific a test, the better it's positive predictive value (Schwartz & Schwartz, 1991). The number of false negative responses therefore affects the sensitivity of a test. (A false negative response is when a subject with a hearing loss is predicted as having normal hearing.) Specificity on the other hand, is affected by the number of false positive responses. (False positive responses refer to the number of subjects with normal hearing that has been identified as having a hearing loss.)

The number of false positive and false negative responses for the prediction of average hearing ability is presented in Tale 5.2.

Table VIII: False positive and false negative responses for the prediction of average hearing at the seven 10dB categories.

False negative responses		False positive responses				
Category 1 (0-10dB)	**Category 2 (11-20dB)**	**Category 3 (21-30dB)**	**Category 4 (31-40dB)**	**Category 5 (41-50dB)**	**Category 6 (51-60dB)**	**Category 7 (61-70dB)**
7%	9%	1%	1%	2%	3%	0%

One aspect that could possibly affect he prediction ability of the neural network, is the amount of data it has to train on. Table IX indicates the number of ears in every one of the seven categories of scenario four for the prediction of average hearing ability.

Table IX: Number of ears in the seven categories of scenario four for prediction of average hearing ability.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
Ears	43	19	13	13	15	16	1

Category seven had only one ear. The fact that there was only one ear in category 7 could possibly have a negative effect on the neural network's capabilities to predict that category accurately, since there were so little data to train on. It was therefore decided to try a new approach on the size of the categories, to attempt to include more ears in the hearing loss categories. Average hearing ability was divided into five categories, the first two spanning 10dB and the hearing loss categories 15dB each. These five categories were presented in Table V. Neural networks that were trained to predict hearing into one of these five categories are referred to as scenario five.

5.2.2 The Prediction of Average Hearing Ability in the Five Categories

The enlargement of categories depicting hearing loss had the desirable effect that more ears were included in the hearing loss categories. The number of ears in every one of the five categories is presented in Table X.

Table X: Number of ears in the five categories of scenario five for the prediction of average hearing ability.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
Number of Ears	43	19	18	23	17

Even though the categories depicting normal hearing (category one and two) still had the greatest number of ears, the other categories had a better representation and the neural network had more data to train on.

The results for the prediction of average hearing in the five categories of scenario five will be discussed next:

Overall prediction ability of the neural network improved to 52% correct predictions (predicted in the correct category). Predictions into an adjacent category were made 28% of the time. Predictions were completely wrong (more than one category wrong) 20% of the time. The neural network was able to predict certain categories much better, especially the two categories depicting normal hearing. Very good hearing (0-10dB) was predicted as such 93% of the time, very good hearing (0-10dB) was predicted as normal (0-20dB) 98% of the time. Normal hearing (0-20dB) was predicted as normal 85% of the time. The results for the predictions of every one of the five categories are presented in Table XI.

Table XI: Results of the neural network's prediction accuracy for prediction of average hearing ability for the five categories of scenario five.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
100% correct	93%	5%	55.5%	35%	24%
one class out	5%	58%	28%	35%	53%
completely wrong	2%	37%	16.5%	30%	23%
0-10dB predicted as <20dB	98%	-	-	-	-
0-20dB predicted as 0-20dB	85%	-	-	-	-

False positive and false negative predictions for the prediction of average hearing ability are presented in Table XII.

Table XII: False positive and false negative responses for average hearing ability at the five categories of scenario five.

False negative responses		False positive responses		
Category 1 (0-10dB)	Category 2 (11-20dB)	Category 3 (21-30dB)	Category 4 (31-40dB)	Category 5 (41-50dB)
4%	7%	1%	5%	2%

By including more data in every category to enable the neural network to have more data to train on even the specificity of the test improved (less false negative responses).

The main aim of this study is to predict hearing ability at the frequencies 500, 1000, 2000 and 4000 Hz. It was decided to take the binary approach one step further, by predicting hearing ability at a specific frequency, one at a time.

5.3 Prediction of 500 Hz

500 Hz were predicted in two scenarios. Scenario four had seven 10dB categories (described in Table IV) and scenario five had five categories (as described Table V).

5.3.1 The Prediction of 500 Hz in Scenario Four.

The results of scenario four where the neural network had to predict 500 Hz within the seven 10dB categories as in Table IV were as follows:

The neural network could predict hearing ability in all seven categories correctly 53.3% of the time. The neural network predicted hearing ability in an adjacent category (the next 10dB span) 23.3% of the time. The network predicted hearing completely wrong (in a category more than one 10dB span away) 23.3% of the time. It was very clear that the neural network could predict certain categories better than others could. It was also interesting to see that the larger the hearing impairment at 500 Hz was, the less accurate the neural network could predict hearing ability. Most accurate predictions were made when hearing ability was perfect (pure tone thresholds (PTTs) 0-10dB) or normal (PTTs 0-20dB). Perfect hearing ability (PTTs 0-10dB) were predicted as perfect (0-10dB) 82% of the time. Perfect hearing ability (PTTs 0-10dB) were predicted as normal (0-20dB) 97% of the time. Normal hearing ability (PTTs 0-20dB) were predicted as normal (0-20dB) 87% of the time. As the hearing loss at 500 Hz increased, the accuracy of the neural network's prediction at 500 Hz decreased. Table XIII presents the results for the prediction accuracy for the seven categories of hearing impairment. Note how the accuracy of the prediction worsens as the hearing loss of 500 Hz increases.

Another aspect that should be noted is the number of false negative responses in Category one and two. Category one (0-10dB) had 12% false negative responses, in other words, subjects with hearing losses were predicted as having perfect hearing 12% of the time. Category two had 8% false negative responses. If the two categories are combined to represent normal hearing (0-20dB), the false negative rate is 20%. This aspect raises questions regarding the sensitivity of this procedure.

Table XIII: Results of the neural network's prediction accuracy at 500 Hz for the seven 10dB categories of scenario four.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
100% correct	82%	19%	0%	22%	0%	0%	0%
one class out	15%	50%	75%	11%	20%	0%	0%
completely wrong	3%	31%	25%	67%	80%	100%	100%
0-10dB predicted as <20dB	97%	-	-	-	-	-	-
0-20dB predicted as 0-20dB	87%	-	-	-	-	-	-

The false positive rate for category 3 (21-30dB) was 1%, category 4 (31-40dB) was 3%, category 5 (41-50dB) was 2%, category 6 (51-60dB) was 3% and category 7 (61-70dB) was 0%. The false positive rate refers to how many subjects with normal pure tone thresholds at 500 Hz were predicted as having a hearing loss.

The false positive and false negative responses for all seven categories are listed in Table XIV.

Table XIV: False positive and false negative responses for 500 Hz at the seven categories of scenario four.

False negative responses		False positive responses				
Category 1 (0-10dB)	Category 2 (11-20dB)	Category 3 (21-30dB)	Category 4 (31-40dB)	Category 5 (41-50dB)	Category 6 (51-60dB)	Category 7 (61-70dB)
12%	8%	1%	3%	2%	3%	0%

The sensitivity and specificity of scenario four will be discusses in more detail in Chapter 6.

Subjects were initially selected in such a way that their average hearing ability fell into one of three categories (40 ears with average hearing ability in the 0-15dB range, 40 ears in the 16-35dB range and 40 ears in the 36-65 dB range). There were however not an equal number of ears in every one of the seven categories at 500 Hz in scenario four due to the fact that many subjects with hearing losses had normal pure tone thresholds (PTTs) at 500 Hz. The number of ears in every one of the seven categories is presented in Table XV.

Table XV: Number of ears in the seven categories of scenario four for 500 Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
Ears	60	26	4	18	5	6	1

Category 1 had the highest number of ears with normal PTTs at 500 Hz, followed by category 2 and category 4. In category 7 (PTTs for 500 Hz between 61-70dB) there were only one ear. This is partly due to the fact that very few people had flat enough audiograms to have a pure tone threshold of >61dB at 500 Hz and still be submitted to the study with a subject selection criteria of average hearing ability of <65dB. (Average hearing ability was determined by calculating the average for 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz). There were only five ears in category 5, only 6 ears in category six and only one ear in category seven. The fact that the neural network had only a few ears to train on in these categories possibly affected the prediction accuracy (no accurate predictions in either one of the three categories were made). It was decided to attempt to predict hearing ability at the categories depicting hearing loss more accurately by including a larger number of ears in each category. The categories depicting hearing loss were therefore enlarged to span 15dB.

5.3.2 Prediction of 500 Hz in Scenario Five.

Scenario five had more ears in every category that presented subjects with hearing loss. The number of ears in every one of the five categories of scenario five is presented in Table XVI. Even though there were still more ears in the normal hearing categories, the neural network had more ears in hearing loss categories to train on.

Table XVI: Number of ears in the five categories of scenario five for 500 Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
Number of Ears	60	26	15	12	7

In scenario five, the neural network could predict hearing ability in all five categories correctly 51% of the time. The neural network predicted hearing ability in an adjacent category (the next 10dB span) 33% of the time. The network predicted hearing completely wrong (more than one category away) 16% of the time. It was again very clear that the neural network could predict certain categories better than others could. Just as in scenario four, the larger the hearing impairment at 500 Hz was, the less accurate the neural network could predict hearing ability. Most accurate predictions were made when hearing ability was very good (PTTs 0-10dB) or normal (PTTs 0-20dB). Very good hearing ability (PTTs 0-10dB) were predicted as such 80% of the time. Very good hearing ability (PTTs 0-10dB) were predicted as normal (0-20dB) 93% of the time. Normal hearing ability (PTTs 0-20dB) were predicted as normal (0-20dB) 92% of the time. Again the accuracy of the neural network's prediction at 500 Hz decreased as the hearing loss at 500 Hz increased. Table XVII presents the results for the prediction accuracy for the five categories of hearing impairment at 500 Hz for scenario five.

Table XVII: Results of the neural network's prediction accuracy at 500 Hz for the five categories of scenario five.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
100% correct	80%	31%	13%	25%	0%
one class out	13%	65%	47%	33%	14%
completely wrong	7%	4%	40%	42%	86%
0-10dB predicted as <20dB	93%	-	-	-	-
0-20dB predicted as 0-20dB	92%	-	-	-	-

There were 11% false negative responses for the first category (0-10dB) and 7% false negative responses for the second category (11-20dB) for the prediction of 500 Hz, scenario five. False positive responses for category 3 were 3%, category 4 had 3% and category five had 0%. These results are summarized in Table XVIII.

Table XVIII: False positive and false negative responses for 500 Hz at the five categories of scenario five.

False negative responses		False positive responses		
Category 1 (0-10dB)	**Category 2 (11-20dB)**	**Category 3 (21-30dB)**	**Category 4 (31-40dB)**	**Category 5 (41-50dB)**
11%	7%	3%	3%	0%

Scenario four made better predictions for normal hearing ability but scenario five were able to make slightly better predictions in areas of severe hearing loss. If category 6 and 7 of scenario four is combined, it spans the same degree of hearing loss (51-70dB) as category five of scenario five. In scenario four, no accurate predictions could be made when subjects demonstrated PTTs >51dB, not even predictions that were one class out. Scenario five could make predictions that were one class out 14 % of the time. It seems that by increasing the number of ears in each category, the neural network had a better prediction ability. It is however very evident that hearing loss at 500 Hz affects the prediction accuracy of the neural network negatively, and that prediction of normal hearing is far better than prediction of hearing loss. The implications for the accuracy of the prediction of 500 Hz will be discussed in Chapter 6.

5.4 Prediction of 1000 Hz

The results of scenario four where the neural network had to predict 1000 Hz within the seven 10dB categories as in Table IV were as follows:

5.4.1 Prediction of 1000 Hz in Scenario Four.

The neural network could predict hearing ability in all seven categories correctly 54% of the time. The neural network predicted hearing ability in an adjacent category (the next 10dB span) 14% of the time. The network predicted hearing completely wrong (in a category more than one 10dB span away) 32% of the time. Just as in the case of 500 Hz, the neural network was able to predict the categories representing normal hearing ability better than those representing hearing impairment. Most accurate predictions were made when hearing ability was perfect (pure tone thresholds (PTTs) 0-10dB) or normal (PTTs 0-20dB). Perfect hearing ability (PTTs 0-10dB) were predicted as perfect (0-10dB) 92% of the time. Perfect hearing ability (PTTs 0-10dB) were predicted as normal (0-20dB) 95% of the time. Normal hearing ability (PTTs 0-20dB) was predicted as normal (0-20dB) 84% of the time. Table XIX presents the results for the prediction accuracy for the seven categories of hearing impairment for the prediction of 1000 Hz.

Table XIX: Results of the neural network's prediction accuracy at 1000 Hz for the seven categories of scenario four.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
100% correct	92%	23%	0%	0%	31%	12.5%	14%
one class out	3%	44%	33%	67%	13%	25%	0%
completely wrong	5%	33%	67%	33%	56%	62.5%	86%
0-10dB predicted as <20dB	95%	-	-	-	-	-	-
0-20dB predicted as 0-20dB	84%	-	-	-	-	-	-

False negative responses for category 1 (0-10dB) was 8% and category 2 had 12% false negative responses. Category 3 had 3% false positive responses, category 4 had 1%, category 5 had 4%, category 6 had 0% and category 7 had 2% false positive responses. The summary of false positive and false negative responses is given in Table XX.

Table XX: False positive and false negative responses for 1000 Hz at the seven categories of scenario four.

False negative responses		**False positive responses**				
Category 1 (0-10dB)	**Category 2 (11-20dB)**	**Category 3 (21-30dB)**	**Category 4 (31-40dB)**	**Category 5 (41-50dB)**	**Category 6 (51-60dB)**	**Category 7 (61-70dB)**
8%	12%	3%	1%	4%	0%	2%

The number of ears in every one of the seven categories is presented in Table XXI.

Table XXI: Number of ears in the seven categories of scenario four for 1000 Hz.

Category	**1 (0-10dB)**	**2 (11-20dB)**	**3 (21-30dB)**	**4 (31-40dB)**	**5 (41-50dB)**	**6 (51-60dB)**	**7 (61-70dB)**
Ears	59	18	9	3	16	8	7

1000 Hz had a slightly better representation of data in the categories representing hearing loss than 500 Hz. It was however decided to enlarge the categories of 1000

Hz as well to attempt to achieve more accurate predictions of categories representing hearing loss.

5.4.2 Prediction of 1000 Hz in Scenario Five.

The number of ears in every one of the five categories of scenario five for the prediction of 1000 Hz is presented in Table XXII.

Table XXII: Number of ears in the five categories of scenario five for 1000 Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
Number of Ears	59	18	9	19	15

The results of the prediction of 1000 Hz in the five categories of scenario five are:

Normal hearing (0-20dB) could be predicted as normal (0-20dB) 87% of the time. Very good hearing (0-10dB) was predicted as normal (0-20dB) 98% of the time. The neural network's overall prediction accuracy of all five categories was 58% correct (within the same category) and 17% within one category. The network predicted 1000 Hz completely wrong 33% of the time. The results for every separate category's prediction accuracy are presented in Table XXIII.

Table XXIII: Results of the neural network's prediction accuracy at 1000 Hz for the five categories of scenario five.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
100% correct	93%	22%	0%	37%	27%
one class out	5%	39%	67%	5%	20%
completely wrong	2%	39%	33%	58%	53%
0-10dB predicted as <20dB	98%	-	-	-	-
0-20dB predicted as 0-20dB	87%	-	-	-	-

There were 9% false negative responses for the first category (0-10dB) and 9% false negative responses for the second category (11-20dB) for the prediction of 1000 Hz, scenario five. False positive responses for category 3 were 2%, category 4 had 3% and category five had 3%. These results are summarized in Table XXIV.

Table XXIV: False positive and false negative responses for 1000 Hz at the five categories of scenario five.

False negative responses			False positive responses	
Category 1 (0-10dB)	Category 2 (11-20dB)	Category 3 (21-30dB)	Category 4 (31-40dB)	Category 5 (41-50dB)
9%	9%	2%	3%	3%

The prediction of 1000 Hz was influenced by the degree of hearing loss as well as the number of ears in every category. These aspects as well as the number of false positive and false negative responses will be discussed in Chapter 6.

5.5 Prediction of 2000 Hz

The results where the neural network had to predict 2000 Hz in the seven categories of scenario four were as follows:

5.5.1 Prediction of 2000 Hz in Scenario Four.

The neural network had an average accurate prediction ability (all seven categories) of 43%. The neural network predicted hearing as being in an adjacent category 25% of the time, and completely wrong (more than one category wrong) 32% of the time. The neural network predicted very good hearing (0-10dB) as such 88% of the time, and normal hearing (0-20dB) as normal (0-20dB) 82% of the time. The network predicted very good hearing ability (0-10dB) as normal (0-20dB) 94% of the time. The results for the separate categories are presented in Table XXV.

False negative responses for category 1 (0-10dB) was only 6% and false negative responses for category 2 (11-20dB) was 15%. False positive responses for category 3 (21-30dB) was 3%, category 4 (31-40dB) 1%, category 5 (41-50dB) 3%, category 6 (51-60dB) 3% and category 7 (61-70dB) 1%. These results are presented in Table XXVI.

Table XXV: Results of the neural network's prediction accuracy at 2000 Hz for the seven categories of scenario four.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
100% correct	88%	15%	0%	0%	24%	19%	0%
one class out	6%	55%	29%	11%	29%	37%	33%
completely wrong	56	30%	71%	89%	47%	44%	67%
0-10dB predicted as <20dB	94%	-	-	-	-	-	-
0-20dB predicted as 0-20dB	82%	-	-	-	-	-	-

Table XXVI: False positive and false negative responses for 2000 Hz at the seven categories of scenario four.

False negative responses		False positive responses				
Category 1 (0-10dB)	Category 2 (11-20dB)	Category 3 (21-30dB)	Category 4 (31-40dB)	Category 5 (41-50dB)	Category 6 (51-60dB)	Category 7 (61-70dB)
6%	15%	3%	1%	3%	3%	1%

The number of ears in every category for the prediction of 2000 Hz in the seven categories of scenario four is presented in Table XXVII.

Table XXVII: Number of ears in the seven categories of scenario four for 2000 Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
Ears	48	20	7	9	17	16	3

2000 Hz had a better representation of data in the categories depicting hearing loss. This is due to the configuration of hearing loss of many of the subjects. Most of the subjects with a hearing loss had better hearing at the lower frequencies and higher degrees of impairment at the higher frequencies. This is a very typical aspect of sensorineural hearing loss (Yantis, 1994). The data of Kimberley et al. (1994) also indicated that the lower frequencies had more available data in the normal hearing areas and a lesser amount of hearing-impaired data. This aspect influenced the accuracy with which the discriminant analysis of these authors could train on, just as it is influencing the training and prediction of this neural network. Even though 2000 Hz had the best representation of data in hearing-impaired categories so far, it was decided to attempt to get an even more accurate prediction of categories depicting hearing-impairment by dividing the data in larger categories. 2000 Hz was therefore also predicted in scenario five.

5.5.2 Prediction of 2000 Hz in Scenario Five.

The number of ears in every one of the five categories of scenario five is presented in Table XXVIII. Category 4 and category 5 have the greatest number of ears in any one of the tests so far.

Table XXVIII: Number of ears in the five categories of scenario five for 2000 Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
Number of Ears	48	20	12	21	19

The results of the prediction of 2000 Hz in the five categories of scenario five were:

The overall prediction capabilities of the network for all five categories was correct 48% of the time, within one class 33% of the time and completely wrong only 19% of the time. Very good hearing (0-10) was predicted as being normal (0-20dB) 96% of the time. Normal hearing (0-20dB) was predicted as normal 84% of the time. The results of every category are presented in Table XXIX. Note that the accuracy of the prediction in category five (51-65dB) was 37% and in the adjacent 15dB category 47% of the time which is considerably better than the results at 500 Hz and 1000 Hz.

Table XXIX: Results of the neural network's prediction accuracy at 2000 Hz for the five categories of scenario five.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
100% correct	88%	15%	8%	24%	37%
one class out	8%	45%	67%	48%	47%
completely wrong	4%	40%	25%	28%	16%
0-10dB predicted as <20dB	96%	-	-	-	-
0-20dB predicted as 0-20dB	95%	-	-	-	-

There were only 4% false negative responses for the first category (0-10dB) and 8% false negative responses for the second category (11-20dB) for the prediction of 2000 Hz, scenario five. False positive responses for category 3 were 1%, category 4 had 5% and category five had 3%. These results are summarized in Table XXX.

Table XXX: False positive and false negative responses for 2000 Hz at the five categories of scenario five.

False negative responses		False positive responses		
Category 1 (0-10dB)	**Category 2 (11-20dB)**	**Category 3 (21-30dB)**	**Category 4 (31-40dB)**	**Category 5 (41-50dB)**
4%	8%	1%	5%	3%

If the number of false positive responses in the first two categories for 500 Hz, 1000 Hz and 2000 Hz are compared, 2000 Hz had the lowest numbers of false negative responses for category one and two so far.

The last frequency that was predicted was 4000 Hz.

5.6 Prediction of 4000 Hz

The prediction of 4000 Hz was also conducted in two scenarios, scenario four with seven 10dB categories, and scenario five with only five categories.

5.6.1 Prediction of 4000 Hz in Scenario Four.

The results of the prediction of 4000 Hz in scenario four are:

The overall average prediction ability of the neural network across all seven 10dB categories was completely accurate 49% of the time, within one 10dB category 23% of the time and completely wrong (more than one 10dB category wrong) 28% of the time. Very good hearing (0-10dB) was predicted as normal (0-20dB) 94% of the time. Normal hearing (0-20dB) was predicted as normal 89% of the time. The results for every separate category are presented in Table XXXI.

Table XXXI: Results of the neural network's prediction accuracy at 4000 Hz for the seven categories of scenario four.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
100% correct	94%	0%	13%	0%	25%	41%	26%
one class out	0%	71%	0%	11%	50%	41%	37%
completely wrong	6%	29%	87%	89%	25%	18%	37%
0-10dB predicted as <20dB	94%	-	-	-	-	-	-
0-20dB predicted as 0-20dB	89%	-	-	-	-	-	-

Category 6 (51-60dB) and category 7 (61-70dB) were predicted most accurately for 4000 Hz, for the seven 10dB categories of scenario four. This might be due to the good representation of hearing impaired data for these categories. The neural network had quite a number of ears to train on in scenario 6 and 7. The numbers of ears for every one of the seven categories are presented in Table XXXII.

Table XXXII: Number of ears in the seven categories of scenario four for 4000 Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-30dB)	4 (31-40dB)	5 (41-50dB)	6 (51-60dB)	7 (61-70dB)
Ears	47	7	8	9	8	22	19

The false positive and false negative responses for the seven categories of scenario four is presented in Table XXXIII. This is the lowest incidence of false negative responses for scenario four at the frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

Table XXXIII: False positive and false negative responses for 4000 Hz at the seven categories of scenario four.

False negative responses		False positive responses				
Category 1 (0-10dB)	Category 2 (11-20dB)	Category 3 (21-30dB)	Category 4 (31-40dB)	Category 5 (41-50dB)	Category 6 (51-60dB)	Category 7 (61-70dB)
6%	3%	2%	1%	0%	0%	3%

5.6.2 Prediction of 4000 Hz in Scenario Five.

For the prediction of 4000 Hz in scenario five, the number of ears in every category is presented in Table XXXIV.

Table XXXIV: Number of ears in the five categories of scenario five for 4000Hz.

Category	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
Number of Ears	47	7	12	13	41

The results of the prediction of 4000 Hz in the five categories of scenario five were as follows:

The overall prediction capabilities of the network for all five categories was correct 63% of the time, within one class 21% of the time and completely wrong only 16% of the time. Very good hearing (0-10) was predicted as being normal (0-20dB) 94% of the time. Normal hearing (0-20dB) was predicted as normal 91% of the time. The results of every category are presented in Table XXXV. Note that the accuracy of the prediction in category five (51-65dB) was 68%. Category four (36-50dB) was predicted within one class all the time and had no complete wrong predictions. This was the best accurate prediction of moderately severe haring loss so far.

Table XXXV: Results of the neural network's prediction accuracy at 4000 Hz for the five categories of scenario five.

Categories	1 (0-10dB)	2 (11-20dB)	3 (21-35dB)	4 (36-50dB)	5 (51-65dB)
100% correct	92%	14%	17%	15%	68%
one class out	2%	57%	25%	85%	15%
completely wrong	6%	29%	58%	0%	17%
0-10dB predicted as <20dB	94%	-	-	-	-
0-20dB predicted as 0-20dB	91%	-	-	-	-

There were 7% false negative responses for the first category (0-10dB) and 3% false negative responses for the second category (11-20dB) for the prediction of 2000 Hz, scenario five. False positive responses for category 3 were 1%, category 4 had 1% and category five had 3%. These results are summarized in Table XXXVI.

Table XXXVI: False positive and false negative responses for 4000 Hz at the five categories of scenario five.

False negative responses		False positive responses		
Category 1 (0-10dB)	Category 2 (11-20dB)	Category 3 (21-30dB)	Category 4 (31-40dB)	Category 5 (41-50dB)
7%	3%	1%	1%	3%

This concludes the prediction of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. In order to visualize all this information, a summary of results will be given in the next section.

5.7 Summary of Results at 500, 1000, 2000 and 4000 Hz

The results of the prediction of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz are have been reported over a number of pages. To better visualize these results, it will be attempted to include all the results for the four frequencies of every scenario into one encompassing table. The results for scenario four for all four frequencies is presented in Table XXXVII. (The symbol (✓) refers to correct predictions, the symbol (✗) refers to wrong predictions and "1out" to predictions in an adjacent category.)

The summary of results for the prediction of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz for scenario five is presented in Table XXXVIII.

Table XXXVII: Summary of the results for 500, 1000, 2000 and 4000 Hz for scenario four.

	500 Hz			1000 Hz			2000 Hz			4000 Hz		
	% ✓	% 1out	% ✗	% ✓	% 1out	% ✗	% ✓	% 1out	% ✗	% ✓	% 1out	% ✗
Category 1 (0-10dB)	82	15	3	92	3	5	88	6	56	94	0	6
Category 2 (11-20dB)	19	50	31	23	44	33	15	55	30	0	71	29
Category 3 (21-30dB)	0	75	25	0	33	67	0	29	71	13	0	87
Category 4 (31-40dB)	22	11	67	0	67	33	0	11	89	0	11	89
Category 5 (41-50dB)	0	20	80	31	13	56	24	29	47	25	50	25
Category 6 (51-60dB)	0	0	100	12.5	25	62.5	19	37	44	41	41	18
Category 7 (61-70dB)	0	0	100	14	0	86	0	33	67	26	37	37
False negative (0-10dB)	12%			8%			6%			6%		
False negative (11-20dB)	8%			12%			15%			3%		
False positive (21-30dB)	1%			3%			3%			2%		
False positive (31-40dB)	3%			1%			1%			1%		
False positive (41-50dB)	2%			4%			3%			0%		
False positive (51-60dB)	3%			0%			3%			0%		
False positive (61-70dB)	0%			2%			1%			3%		
Overall prediction accuracy	53.3%			54%			43%			49%		
Overall one category out	23.3%			14%			25%			23%		
Overall wrong	23.3%			32%			32%			28%		
0-10dB as normal (0-20dB)	97%			95%			94%			94%		
0-20dB as normal (0-20dB)	87%			84%			82%			89%		

Table XXXVIII: Summary of the results for 500, 1000, 2000 and 4000 Hz for scenario five.

	500 Hz			1000 Hz			2000 Hz			4000 Hz		
	% ✓	% 1out	% ✗	% ✓	% 1out	% ✗	% ✓	% 1out	% ✗	% ✓	% 1out	% ✗
Category 1 (0-10dB)	80	13	7	93	5	2	88	8	4	92	2	6
Category 2 (11-20dB)	31	65	4	22	39	39	15	45	40	14	57	29
Category 3 (21-35dB)	13	47	40	0	67	33	8	67	25	17	25	58
Category 4 (36-50dB)	25	33	42	37	5	58	24	48	28	15	85	0
Category 5 (51-65dB)	0	14	86	27	20	53	37	47	16	68	15	17
False negative (0-10dB)	11%			9%			4%			7%		
False negative (11-20dB)	7%			9%			8%			3%		
False positive (21-35dB)	3%			2%			1%			1%		
False positive (36-50dB)	3%			3%			5%			1%		
False positive (51-65dB)	0%			3%			3%			3%		
Overall prediction accuracy	51%			58%			48%			63%		
Overall one category out	33%			17%			33%			21%		
Overall wrong	16%			33%			19%			16%		
0-10dB as normal (0-20dB)	93%			98%			96%			94%		
0-20dB as normal (0-20dB)	92%			87%			84%			91%		

To better visualize the results of the prediction of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz in scenario four, it is presented schematically in the form of a histogram in Figure 5.1. The zero (0) domain value on the histogram represents the number of correct predictions (within the same category). The minus one domain value (-1) on the histogram represents the number of predictions that were made in one adjacent category, depicting better hearing than the subject's actual hearing. The minus two (-

2) domain value depicts predictions two categories to the less hearing-impaired side, and so forth. The positive one (1) domain value on the histogram represents the number of predictions that were made in one adjacent category depicting greater hearing impairment. The positive two (2) domain value represents predictions that were made two categories to the more hearing- impaired side, and so forth. The green area represents the standard deviation.

The histogram representing the results for the prediction of 500 Hz, 1000 Hz, 2000 H and 4000 Hz, scenario five, is illustrated in Figure 5.2.

The histogram for the prediction of average hearing ability is illustrated in Figure 5.3.

5.8 The Effects of Age and Gender on the Distortion Product

To determine the possible effect of age and gender on the distortion product, it was decided to include these factors as input stimuli in the neural network. The variables age and gender were included in a neural network run of scenario four where the network had to predict average hearing ability. (Average hearing ability refers to the average of 500Hz 1000 Hz, 2000 Hz and 4000 Hz, as described Chapter 4.) The influence of age and gender were therefore not tested for each individual frequency, but on the prediction of average hearing to determine its effect on the distortion product.

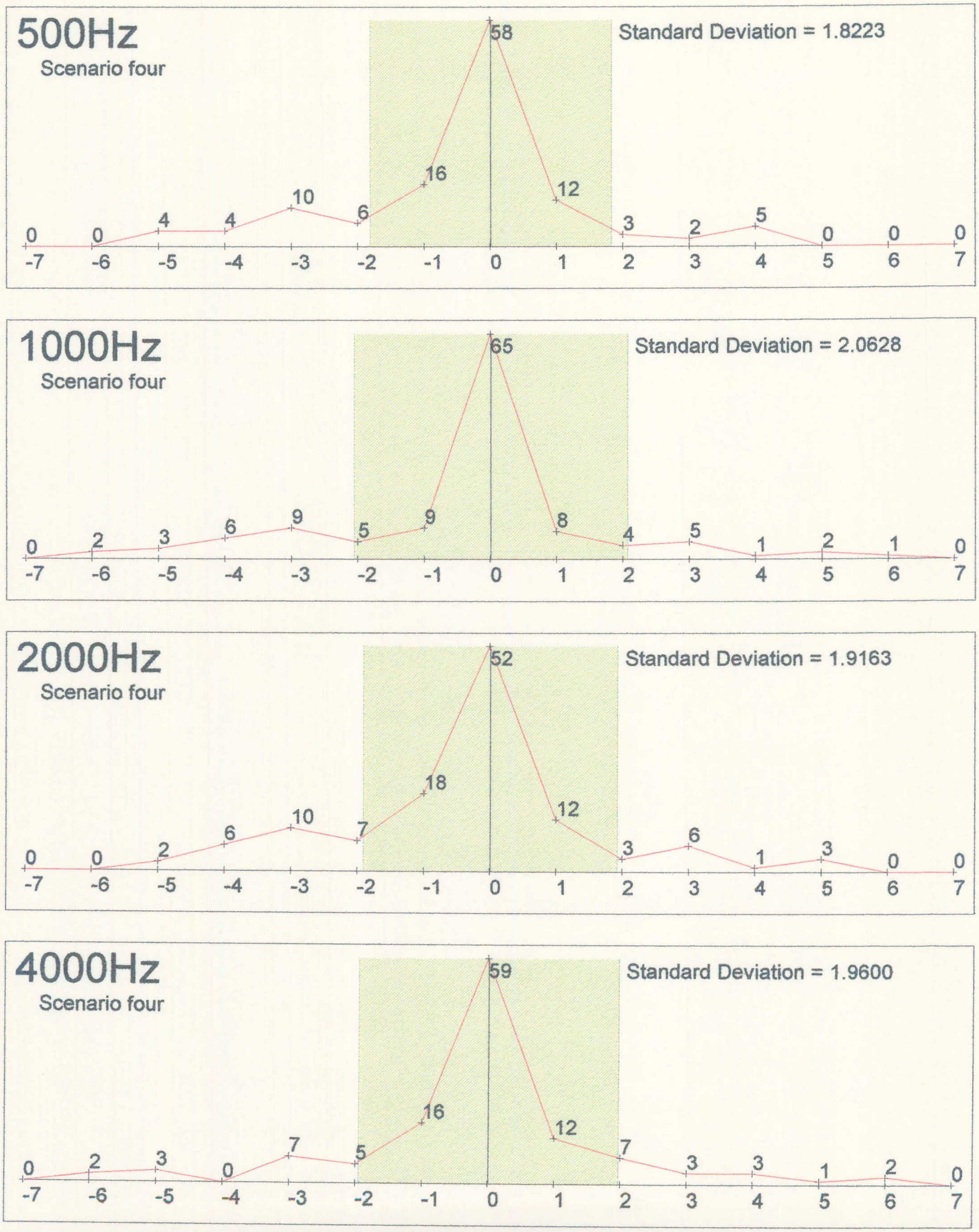

Figure 5.1: Accuracy of the neural network prediction at 500Hz, 1000Hz, 2000Hz and 4000Hz, scenario four.

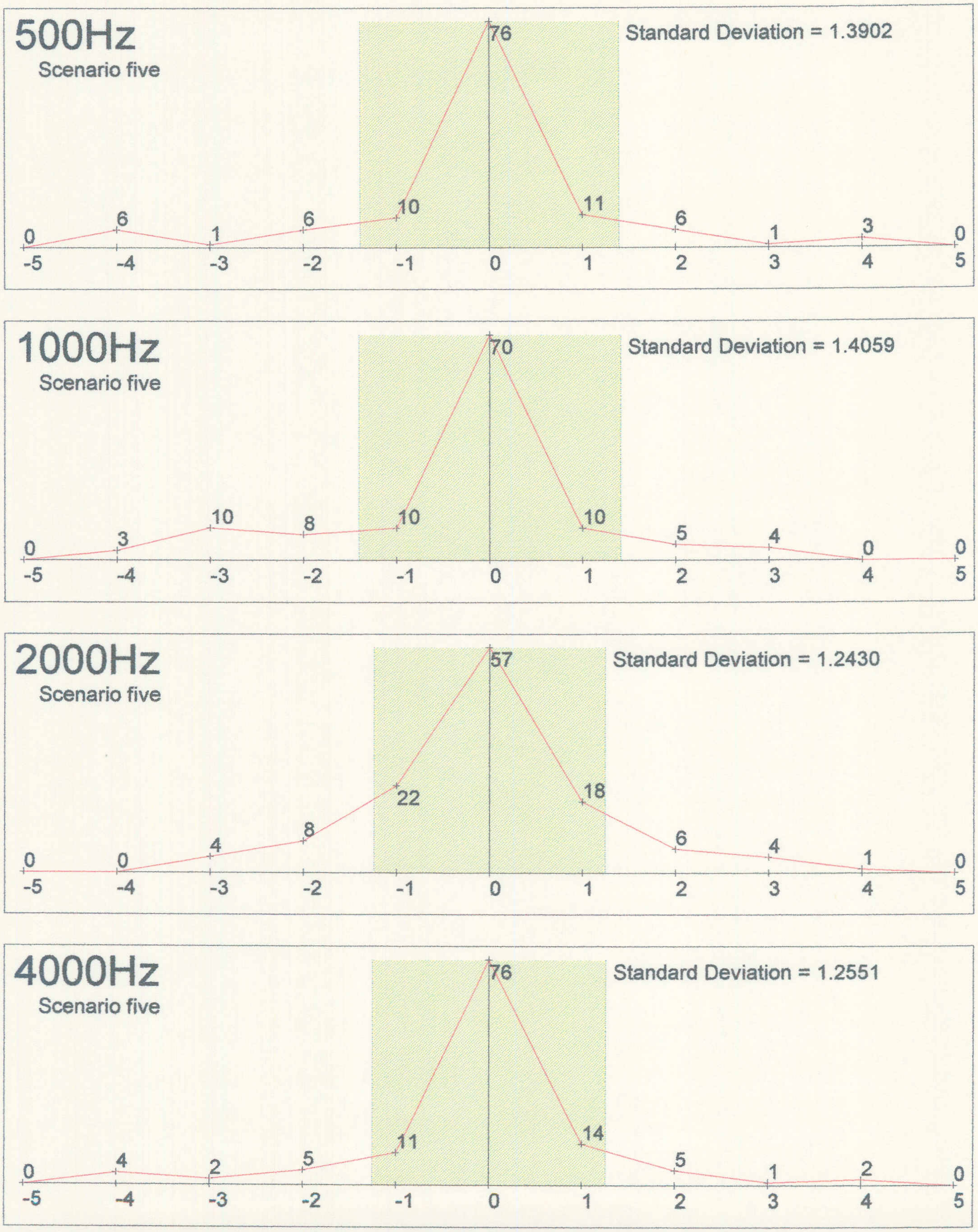

Figure 5.2: Accuracy of the neural network prediction at 500Hz, 1000Hz, 2000Hz and 4000Hz, scenario five.

5.8.1 The Effect of Gender

Gender had a slight positive effect on the prediction abilities of the neural network. The prediction of average hearing with the age variable included resulted in slightly more accurate prediction. The results for the overall prediction accuracy for the seven 10dB categories are presented in Table XXXIX.

Table XXXIX: Prediction of average hearing ability with DPOAEs and gender.

	Average hearing without gender	Average hearing with gender
Right (in same category)	40%	44%
In an adjacent 10dB category	30%	29%
Completely wrong	30%	27%

When the gender variable was included in the neural network, prediction accuracy for predictions in the same 10dB class (correct predictions) improved from 40% to 44%. The number of predictions in the adjacent 10dB class worsened from 30% to 29%. When correct predictions and predictions in adjacent categories are combined, results for the two neural network runs differ with only 3%. With the gender variable, predictions for correct or adjacent categories were 73% and without the gender variable it was 70%.

The gender variable influenced prediction accuracy in all seven 10dB categories. It seems that the gender variable improved the prediction of hearing ability in categories 2 and 4 and had a lower incidence of false negative predictions in category one. All these results are summarized in Table XLIII.

5.8.2 The Effect of Age

Age affected the prediction of average pure tones with DPOAEs positively. Markedly better predictions were made when the age variable was included. Prediction accuracy for correct predictions (in the same 10dB category) improved from 40% (without age effect) to 50%. Predictions in an adjacent 10dB category worsened from 30% to 24%. These results are presented in Table XL.

Table XL: Prediction of average hearing ability with DPOAEs and age.

	Average hearing without age	Average hearing with age
Right (in same category)	40%	50%
In an adjacent 10dB category	30%	24%
Completely wrong	30%	26%

The effect of age on the prediction of the seven 10dB categories is clearly seen in the improvement of predictions across five of the seven categories (2 categories, namely 6 and 7 remained the same). These results are presented in Table XLIII.

The fact that there were more input neurons increased the complexity of the neural network slightly. To investigate if this increased complexity had a negative effect on the prediction accuracy of the neural network, another network run was conducted with more middle level neurons. The number of middle level neurons was increased from 140 to 165. Prediction error during training was kept at 5%. The network therefore had 97 input nodes, 165 middle neurons and seven output neurons (one for every 10dB category). Average hearing without any extra variables, as well as the influence of age on the prediction of average hearing was predicted with this increased set of middle neurons. Results indicated that the increased number of middle level neurons did not improve the predictions. It was therefore decided to keep the middle level neurons at 140, not to add another variable that might influence the data.

5.8.3 The Effect of Age and Gender Combined

Results indicated slightly less accurate predictions compared to that of the prediction with the age variable alone. Predictions were correct 48% of the time, within one category 23% of the time and completely wrong 29% of the time. These results are presented in Table XLI.

Table XLI: Prediction of average hearing ability with the combined effects of gender and age.

	Average hearing without age	Combined effects of age and gender
Correct (in same category)	40%	48%
In an adjacent 10dB category	30%	23%
Completely wrong	30%	29%

To summarize the results of the influence of age and gender on the overall prediction accuracy of the neural network the results are presented in Table XLII.

Table XLII: Summary of the prediction of average hearing ability and the effects of age and gender on prediction accuracy:

	Average hearing alone	Average hearing with gender	Average hearing with age and gender	Average hearing with age
Correct (in the same category)	40%	44%	48%	50%
In adjacent 10dB category	30%	29%	23%	24%
Wrong (more than one category out)	30%	27%	29%	26%

Even though the age variable alone had the best overall prediction accuracy, the combined effects of age and gender had the most accurate predictions of very good hearing (0-10dB). The combined effects of age and gender also predicted normal hearing (0-20dB) as normal most accurately (90% of the time). The gender variable alone only improved the number of false negative responses in category 1 but did not have drastic positive effect on the prediction accuracy of the neural network in any of the other categories, only a slight positive effect in category 2). In some of the categories it had a slight negative effect (category 3 and 5). The age variable alone had a drastic improvement in prediction accuracy in most of the categories. The summary of the influence of all these variables on every one of the seven 10dB categories is presented in Table XLIII.

To illustrate the differences in neural network predictions with the inclusion of age and gender, these results are presented in a histogram in Figure 5.3. Again, the zero (0) domain value on the histogram represents the number of correct predictions (within the same category). The minus one domain value (-1) on the histogram represents the number of predictions that were made in one adjacent category, depicting better hearing than the subject's actual hearing. The minus two (-2) domain value depicts predictions two categories to the less hearing-impaired side, and so forth. The positive one (1) domain value on the histogram represents the number of predictions that were made in one adjacent category depicting greater hearing impairment. The positive two (2) domain value represents predictions that were made two categories to the more hearing- impaired side, and so forth. The green area represents the standard deviation.

Table XLIII: Summary of the effects of age and gender on the seven 10dB categories of scenario four

	Average hearing alone			**Average hearing with gender**			**Average hearing with age and gender**			**Average hearing with age**		
	% ✓	**% 1out**	**% ✗**	**% ✓**	**% 1out**	**% ✗**	**% ✓**	**% 1out**	**% ✗**	**% ✓**	**% 1out**	**% ✗**
Category 1 (0-10dB)	**91**	9	0	**91**	7	2	**98**	2	0	**93**	7	0
Category 2 (11-20dB)	**11**	58	31	**16**	63	21	**21**	63	16	**26**	48	26
Category 3 (21-30dB)	**23**	54	23	**15**	46	39	**23**	31	46	**31**	38	31
Category 4 (31-40dB)	**0**	31	69	**0**	62	38	**8**	31	61	**8**	38	54
Category 5 (41-50dB)	**27**	20	53	**20**	33	47	**27**	40	33	**40**	27	33
Category 6 (51-60dB)	**25**	31	44	**25**	37.5	37.5	**25**	12	63	**25**	19	56
Category 7 (61-70dB)	**0**	100	0	**0**	0	100	**0**	100	0	**0**	100	0
False negative (0-10dB)	7			3			2			3		
False negative (11-20dB)	9			9			11			10		
False positive (21-30dB)	1			3			3			2		
False positive (31-40dB)	1			1			1			1		
False positive (41-50dB)	2			2			1			3		
False positive (51-60dB)	3			2			1			0		
False positive (61-70dB)	0			0			0			0		
0-10dB as normal (0-20dB)	100			98			100			100		
0-20dB as normal (0-20dB)	87			87			90			89		

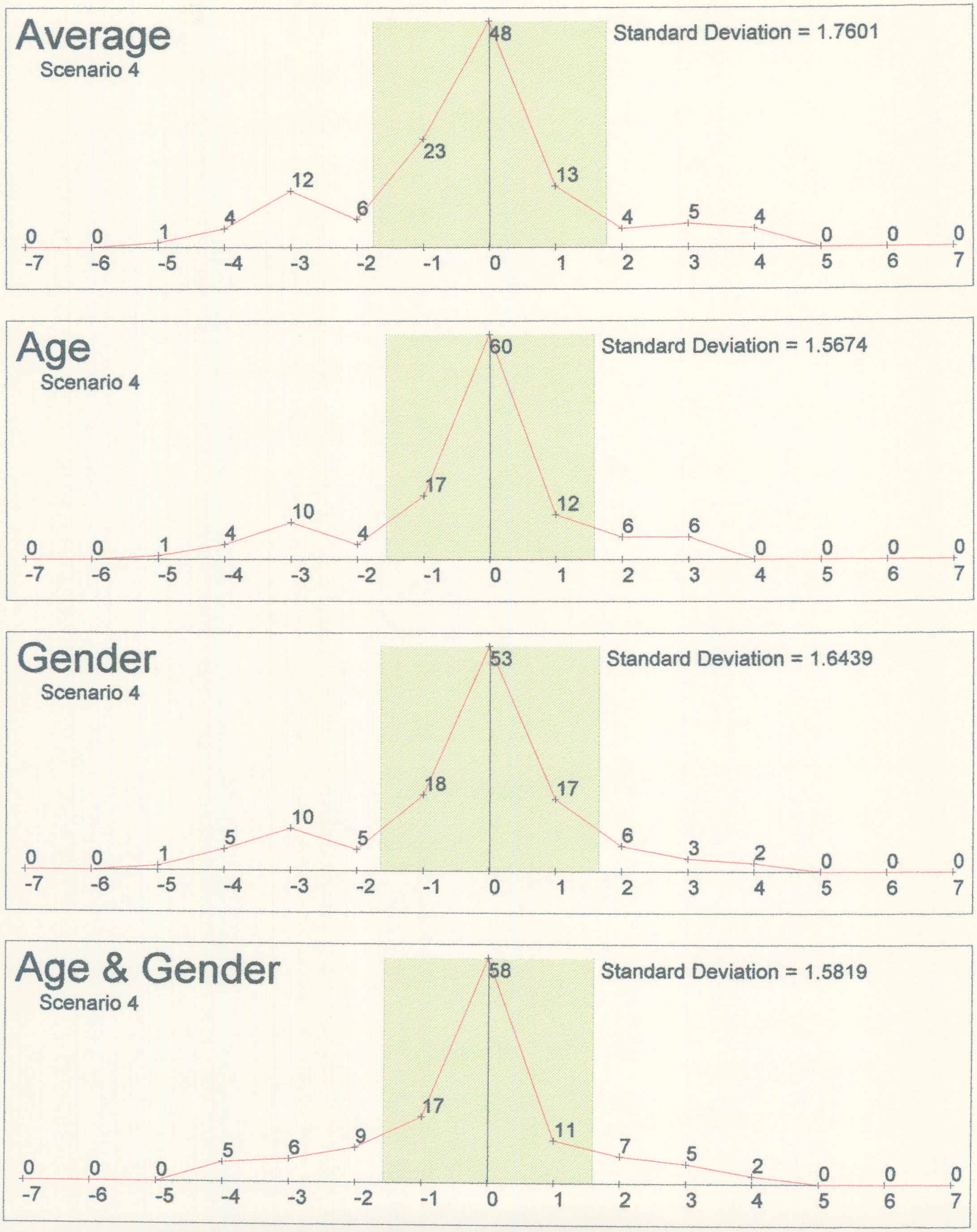

Figure 5.3: Prediction accuracy of average hearing ability when the age and gender variables are included.

5.9 Summary of Results

ANNs were used to predict hearing ability given only DPOAEs. Hearing ability was predicted at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz as well as average hearing ability at these four frequencies. Neural networks were also used to investigate the effect of age and gender on the prediction accuracy of a neural network given distortion product otoacoustic emissions.

There are different ways to interpret the results obtained from these neural networks. The overall prediction accuracy of a neural network across all the categories can be determined or categories can be analyzed separately. When overall prediction accuracy across all categories are determined, results do not seem very impressive. Best overall prediction capabilities were measured at 4000 Hz (scenario five), which was 63% and second best prediction at 1000 Hz (scenario five), which was 58%. The worst overall prediction capabilities were measured at 2000 Hz (scenario four), namely 43%. The largest completely wrong predictions (more than one category out) were also measured at 1000 Hz (scenario five) which was 33% while 500 Hz and 4000 Hz (both at scenario five) had the least completely wrong predictions, 16%.

When categories are analyzed separately, results improve substantially for some of the categories. Categories one and two, depicting normal hearing (0-20dB) revealed the best results. Best prediction of normal hearing were measured at 500 Hz (scenario five) where the neural network correctly predicted normal hearing as normal 92% of the time. Worst prediction of normal hearing was 82% measured at 2000 Hz (scenario four).

The inclusion of the age and gender variables yielded interesting results. With the inclusion of the combination of age and gender, the prediction of very good average hearing (0-10dB) was phenomenal, namely 98% and it had a very low false negative rate of 2%. The inclusion of age yielded better overall prediction across all the categories and also lowered false negative responses in category one.

Specific predictions of decibel values for pure tone thresholds that indicated hearing impairment were rather disappointing. With closer analysis it is evident that there is a negative correlation between prediction of pure tone thresholds and hearing loss. The larger the hearing impairment, the less accurate the prediction of hearing ability. Another aspect that influenced prediction accuracy considerably was the number of ears in every category and the amount of data the neural network had to train on. The greater number of ears included in a category, the better the ability of the neural network to predict that category correctly.

The technique that was used in this study namely to use the pattern of all present and absent DPOAE responses for 8 DP Grams yielded very interesting and rewarding results nevertheless. The neural network was able to predict normal hearing very accurately, even in the case of 500 Hz. This is an exiting improvement in the prediction of hearing ability, especially the prediction of frequencies lower than 1000 Hz, which did not yield satisfactory results in the past (Gorga et al., 1996; Gorga et al., 1993; Kimberley et al., 1994). The differences in results between previous studies and this study will be discussed in Chapter 6.