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Concurrent Vowel Identification and Speech Perception in Noise in Individuals With Cochlear Hearing Loss, U Ajith Kumar, Praveen Rayanagoudar and Arivudai Nambi, *Acta Acustica* **vol. 99** (Number 6), 2013, pp. 952-959

DOI

<https://doi.org/10.3813/AAA.918674>

Concurrent Vowel Identification and Speech Perception in Noise in Individuals With Cochlear Hearing Loss

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Summary

Previous studies have indicated that individuals with cochlear hearing loss perform poorly in concurrent vowel identification task. This indicates that individuals with cochlear hearing loss do not use F0 cues to segregate two acoustic streams, as much as normal hearing individuals do. However, which of vowel features (place, tongue height etc.), are better transmitted when the F0s of two concurrently presented vowels are varied is not known. Moreover, the contribution of stream segregation abilities in understanding of speech in the presence of competing signal is also not clear. Hence, this study aimed to evaluate the relationship between concurrent vowel identification scores and speech perception abilities in noise in individuals with cochlear hearing loss and compared that to normal hearing individuals. Specifically, we measured the identification of vowels /e/, /i/, /o/ and /u/ when vowel /a/ was presented simultaneously as a competing stimulus in 14 individuals with normal hearing and 15 individuals with cochlear hearing loss. Vowel identification scores were measured in four conditions: with 0 semitone difference between fundamental frequencies of concurrent vowels, with 1 semitone, 2 semitone and 4 semitone difference in the fundamental frequencies of concurrent vowels. Signal to noise ratio required to identify 50% of presented speech (SNR-50) in presence of four talker babble was also measured using standardized sentence list. Furthermore, relationship between concurrent vowel identification and SNR-50 was also evaluated. The results of the present study showed that individuals with cochlear hearing loss had poorer concurrent vowel identification scores compared to the normal hearing group, especially in 0 semitone difference condition. There were significant correlations between concurrent vowel identification scores and SNR-50 indicating, differences in the F0 are one of the most robust cues for stream segregation.

PACS no. 43.71.-k, 43.71.Es, 43.71.Ky

1. Introduction

Hearing impaired individuals often report of inability to understand speech especially, in the presence of background noise [1, 2, 3]. Turner, Fabry, Barrett and Horwitz [4] reported that individuals with cochlear hearing loss required larger signal to noise ratio (SNR) to understand target speech when compared to normal hearing individuals. Furthermore, it has been shown that cochlear hearing loss individuals demonstrate poor identification of consonants and vowels in both quiet and noisy conditions compared to normal hearing individuals [3, 5, 6, 7]. Poor speech perception in individuals with cochlear hearing has been attributed to deficits in spectral and temporal processing (e.g.: [8]). Due to poor frequency and temporal resolution individuals with cochlear hearing loss finds it difficult to

resolve spectral peaks and troughs or to extract the target from the masker. It has been shown that individuals with cochlear hearing loss have poor frequency selectivity, temporal fine structure processing and have less fluctuating masker benefit [9]. Typically when listening in the quiet situation, listeners rely mostly on spectral cues i.e., the energy peaks of formants coded by the place of activation along the basilar membrane for vowel identification [10]. Competing voice masks the spectral information and hence ability to use the spectral information is reduced. In such situation, temporal cues such as changes in fundamental frequency of the voice (F0) may aid in perception. The fundamental frequency plays an important role in the perceptual segregation of simultaneous as well as non-simultaneous sources [11, 12]. Individual's ability to use the F0 cues in differentiate two stimuli can be assessed by concurrent or double vowel identification [13, 14]. In this listener's ability identify the monaural simultaneous presentation of two vowels are evaluated.

Received 6 October 2012,
accepted 2 August 2013.

De Cheveigne [15] investigated the segregation of concurrent vowel based on the waveform interaction in terms of delta F0's. The changes (improvement) were observed in the segregation of concurrent vowel identification for the delta F0's as low as 0.4%. However, significant improvement in the identification of concurrent vowels was observed at a higher delta F0's. Vongpaisal and Pichora-Fuller [10] studied the effect of age on concurrent vowel identification in normal hearing individuals in younger and older adults. They found significant improvement in the concurrent vowel identification with a increase in the F0 up to 2 semitone differences and levelled off after an increase of more than 2 semitone difference. Arehart, Rossikatz and Swensson-Prutsman [16] studied the concurrent vowel perception in listeners with cochlear hearing loss and in individuals with normal hearing. The F0 was varied from 0 to 4 semitones. In all the conditions, individuals with cochlear hearing loss performed significantly poorer than normal hearing individuals. When deltaF0 is 0 semitones, listeners in hearing impaired group often perceived the presence of only 1 vowel, whereas listeners in normal hearing group generally perceived presence of 2 vowels. The results supported the idea of increased susceptibility to masking as the primary factor underlying the degraded perception of vowels in listeners with cochlear hearing loss. Different models have been developed to explain the mechanisms of concurrent vowel identification. All the models assume some kind of template matching mechanism at the central system. Cochlear excitation patterns are used in place models for the purpose of template matching [17]. Periodicity based F0 segregation models assumes that the listener would segregate competing vowels based on two distinct periodicities [15].

Above studies have indicated that individuals with cochlear hearing loss perform poorly in concurrent vowel identification task. This indicates that individuals with cochlear hearing loss do not use F0 cues to segregate two acoustic streams, as much as normal hearing individuals do. However, which of vowel features (place, tongue height etc) are better transmitted when the F0s of two concurrently presented vowels are varied is not known. Moreover, it is not clear how much the ability to use F0 cues to separate two vowels contributes to understanding of speech in presence of competing signal. Hence, this study aimed to evaluate the relationship between concurrent vowel identification scores and speech perception abilities in noise in individuals with cochlear hearing loss and compared that to normal hearing individuals. Concurrent vowel identification task evaluates the listeners' ability to use F0 cues without any confounding linguistic factors. Hence this task is preferred over other tasks such as sentence or word recognition task in the presence of competing signal with different F0. Specifically, we measured the identification of vowels /e/, /i/, /o/ and /u/ when vowel /a/ was presented simultaneously as a competing stimulus. Signal to noise ratio required to identify 50% of presented speech (SNR-50) in the presence of four talker babble was also measured. Furthermore, the relationship between concurrent vowel identification and SNR-50 was also evaluated.

2. Method

2.1. Participants

Participants were assigned to one of the two groups based on the criteria established through audiometric evaluations. The first group consisted of 15 individuals with normal hearing sensitivity. All participants in this group had normal hearing sensitivity with four frequency pure tone average (average of thresholds at 500 Hz, 1 kHz, 2 kHz and 4 kHz) below 15 dB HL. Their age ranged from 36 years to 58 years. Immittance evaluation in the ear to be tested revealed 'A' type tympanogram with the presence of auditory reflex thresholds within normal limits. Individuals were able to perform an open set speech identification testing and had a score of more than 80%. The participants had no other significant history of any neurological or cognitive deficits that was ascertained through a structured interview.

The second group consisted of 14 individuals with hearing loss. All the participants in the experimental group had moderate to moderately severe sensori-neural hearing loss. They had an air-bone gap of less than 10 dB HL. The participants' age ranged from 36 years to 64 years. Immittance evaluation in the ear to be tested revealed 'A' type tympanogram with present/elevated/absent auditory reflex thresholds. The individuals were able to perform an open set speech identification testing and had scores proportionate to the audiometric hearing loss. The participants had no other significant history of any neurological or cognitive deficits that was ascertained through a structured interview and Mini mental status examination. Two sentence list form speech test developed by Methi, Avinash and Kumar [18] was used to measure the speech identification scores in both the normal and cochlear hearing loss group. Independent samples t test showed that there was no statistically significant difference between the mean speech identification scores of both the groups in quiet ($t = 0.83$, $p > 0.05$). The results of basic audiological tests in individuals with cochlear hearing loss are summarized in Table XVI.

2.2. Concurrent vowel identification

2.2.1. Signal processing

Five vowels /a/, /e/, /i/, /o/, /u/ were synthesized at the sampling rate of 44,100 Hz, using the Klatt synthesizer. Each vowel was synthesized with a base F0 of 220 Hz. All the five vowels were once again synthesized with different F0 which corresponded to 1, 2, and 4 semitones increase from base F0 (e.g.: -1 semitone increase from 220 Hz corresponds to 238.3 Hz). Each vowel had a duration of 290 ms with 20 ms raised cosine onset/offset ramps. All synthesized vowels were scaled to same amplitude. The formant characteristics of the vowels used for the concurrent vowel identification task are given in the Table I. These values considered based on the normative study by Hillenbrand, Getty, Clark and Wheeler [19].

2.2.2. Procedure

Identification task was carried out separately for each semitone F0 condition. The listeners were first familiarized with all the vowels in a single vowel identification task. In the familiarization task, listeners heard five repetitions of all the vowels in base F0 and semitones varied conditions. Feedback was provided for each response. It was made sure that participants were able to identify the vowels in isolation with 100% accuracy before the actual testing commenced. For the purpose of concurrent vowel identification, the vowels were paired with each other. The same vowels were not paired even though, they had different F0. Vowel /a/ was kept constant and other vowels were variable which were considered as target stimuli. Vowels within the pair were presented simultaneously to one ear at a time. APEX software [20] was used to present the randomized stimulus. Concurrent vowel identification was done at four different conditions. In all the four conditions, vowel /a/ with a base F0 (220 Hz) was kept constant. Whereas, the variable vowels had F0 that were varied in (/i/, /u/, /o/ and /e/) semitone levels. In the first condition both the vowel /a/ and variable vowels were presented at base F0. This resulted in 0 semitone difference between the F0 of two concurrently presented vowels. In second condition, F0 of the variable vowels were increased by 1 semitone (238.3 Hz). In third and fourth condition F0 of variable vowels were increased to 2 semitone levels (256.6 Hz) and 4 semitone levels (292.2 Hz) respectively. In all conditions F0 of the vowel /a/ was maintained at 220 Hz.

Participants were seated in a quiet room in front of a computer monitor. The four variable vowels (/i/, /u/, /o/, /e/) appeared on the screen. Variable vowels and vowel /a/ with base F0 were presented through Sennheisser HD449 circum-aural headphones. Stimulus was presented monaurally to the participants' at the most comfortable level. Participants were instructed to click on the corresponding vowel button on the computer screen. Each of the four variable vowels was presented 10 times in a randomized order. This resulted in a total of 40 presentations in each of the semitone condition and a total of 160 presentations for all 4 semitone difference conditions. Participants were encouraged to guess if they were not sure. The results were arranged in confusion matrices for analysis.

2.3. Speech perception in noise

Speech perception in noise was evaluated using the speech in noise test developed by Methi, Avinash and Kumar [18]. Two equivalent lists from the original test were selected for the present study. Each list contained 7 sentences mixed with the four talker speech babble noise at different signal to noise ratios (SNRs). The first sentence in the each list was at +20 dB SNR, second sentence was at +15 dB SNR, third sentence was at +10 dB SNR, fourth sentence was at +5 dB SNR, fifth sentence was at 0 dB SNR, sixth sentence was at -5 dB SNR and last sentence was at -10 dB SNR. Each sentence had 5 key words. These sentences were presented through a personal computer (Lenovo Z372) at comfortable levels us-

Table I. Formant frequency values of different vowels used in the experiment.

Vowel	F1	F2	F3
/a/	936	1551	2815
/i/	437	2760	3372
/u/	459	1105	2735
/o/	555	1035	2828
/e/	536	2530	3047

Table II. Stimulus response matrix for 0 semitone difference in normal hearing group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	41	20	34	16
i	3	110	1	2
o	80	3	89	77
u	26	17	26	55
total	150	150	150	150

Table III. Stimulus response matrix for 1 semitone difference in normal hearing group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	91	11	3	13
i	0	132	1	2
o	48	1	135	102
u	11	6	11	33
total	150	150	150	150

ing Sennheisser HD449 circum-aural headphones. The listener's task was to repeat the sentences presented and each correctly repeated key word was awarded one point for a total possible score of 35 points per list.

3. Results

3.1. Concurrent vowel identification

3.1.1. Confusion matrices

Separate stimulus-response matrices were constructed for each semitone conditions for both the normal hearing and the cochlear hearing loss group. In these matrices (Tables II–IX), the number in each cell is the frequency with which each stimulus-response pair occurred. The number of correct responses may be obtained by totalling the frequency along the main diagonal. Tables II–V show the stimulus response matrices of vowel identification scores in normal hearing group for zero semitone, one semitone, two semitone and four semitone differences in fundamental pitch respectively. Tables VI–IX depict the same information in the cochlear hearing loss group.

From the confusion matrices it can be inferred that vowel /i/ was perceived better compared to other vowels in normal hearing listeners. It was also observed that in cochlear hearing loss group for zero semitone difference condition

Table IV. Stimulus response matrix for 2 semitone difference in normal hearing group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	132	3	8	9
i	0	143	1	4
o	15	2	126	46
u	3	2	15	91
total	150	150	150	150

Table V. Stimulus response matrix for 4 semitone difference in normal hearing group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	116	1	12	7
i	2	147	0	3
o	10	1	95	18
u	22	1	43	122
total	150	150	150	150

Table VI. Stimulus response matrix for 0 semitone difference in cochlear hearing loss group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	36	26	32	24
i	16	52	38	27
o	50	29	44	52
u	38	33	26	37
total	140	140	140	140

- i. Vowel /e/ was confused with /o/,
- ii. vowel /u/ was confused with /o/.

Vowel identification scores of normal hearing subjects were above chance level (25% or score of 37.5) in all the condition. But identification of vowels were below chance level in hearing impaired group for vowels /e/ and /u/ in 0 semitone difference and 1 semitone difference conditions. However, as the differences in the pitch between target and that interfering vowel increased vowel identification scores improved and confusion decreased in both the groups. However, the amount of improvement was more in the normal hearing group than the cochlear hearing loss group.

3.1.2. d-prime scores

d-prime scores were calculated from the vowel identification scores. Three-way ANOVA with repeated measures were performed to investigate the main effect of, semitones, vowels and hearing status on vowel identification. There was a significant main effect of semitones ($F(3, 81) = 34.52, p < 0.05$), vowels ($F(3, 81) = 44.87, p < 0.05$) and hearing status ($F(1, 27) = 83.1, p < 0.05$) on vowel identification ability. There was a significant interaction found between semitones and hearing status ($F(3, 81)$

Table VII. Stimulus response matrix for 1 semitone difference in cochlear hearing loss group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	28	30	19	15
i	26	50	14	23
o	53	27	69	71
u	33	33	38	31
total	140	140	140	140

Table VIII. Stimulus response matrix for 2 semitone difference in cochlear hearing loss group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	43	27	26	28
i	32	43	9	17
o	43	30	62	51
u	22	40	43	44
total	140	140	140	140

Table IX. Stimulus response matrix for 4 semitone difference in cochlear hearing loss group. The number in each cell reflects the combined responses from all the subjects.

	e	i	o	u
e	46	25	26	32
i	35	80	25	18
o	22	11	41	29
u	37	24	48	61
total	140	140	140	140

$= 17.28, p < 0.05$), vowels and hearing status ($F(3, 81) = 18.46, p < 0.05$) as well as vowels and semitones ($F(9, 243) = 3.98, p < 0.05$). Since, there was significant interaction among the independent variables, follow up one way ANOVA with repeated measures were performed to investigate the main effect of semitones on vowel identification in both subject groups separately.

One-way ANOVA with repeated measures did not show a significant main effect of semitones on sensitivity of the hearing impaired individuals to identify vowels /e/ ($F(3, 39) = 1.38, p > 0.05$) and /o/ ($F(3, 39) = 1.26, p > 0.05$). Hearing impaired individual's sensitivity to identify vowels significantly more for vowels /i/ ($F(3, 39) = 4.01, p > 0.05$) and /u/ ($F(3, 39) = 3.50, p > 0.05$) when F0 difference was increased. Mean d-prime values for each vowel with different semitones are given in Figure 1. Except for vowel /i/ hearing impaired individuals did not show sensitivity for any vowels in 0 semitone conditions. In 1 semitone condition, sensitivity to vowel /o/ was present however; vowel /e/ and /u/ had no sensitivity. Hearing impaired individuals exhibited sensitivity to identify all vowels in 2 and 4 semitone condition.

Normal hearing individuals exhibited reasonably good sensitivity from 0 semitones onwards. One way ANOVA

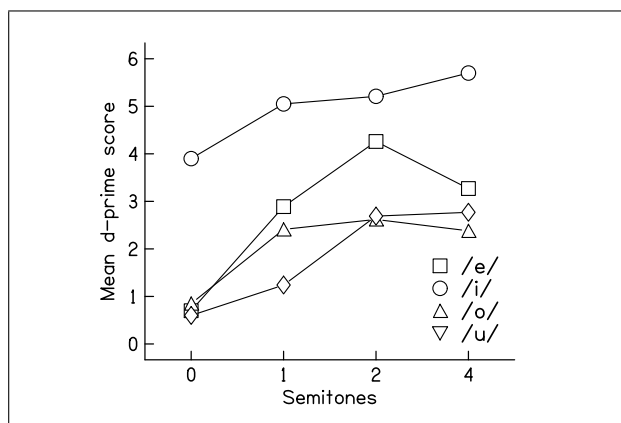


Figure 1. Mean d-prime scores for different vowels across different semitones in normal hearing listeners.

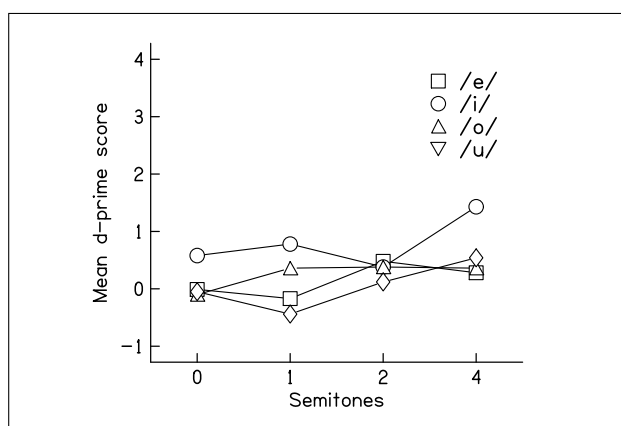


Figure 2. Mean d-prime scores for different vowels across different semitones in hearing impaired listeners.

with repeated measures revealed that, sensitivity to vowel identification significantly increased with increase in F0 difference. For vowels /i/ and /o/ sensitivity at 4 semitone difference was not significantly different from sensitivity at 1 and 2 semitone differences. However, sensitivity at 0 semitone differences was significantly lower than the sensitivity at 4 semitone difference for both vowels. For vowel /u/ sensitivity increased when 1 semitone difference was introduced. Beyond 1 semitone difference, there was no further change in the sensitivity. Sensitivity to identify vowel /e/ significantly increased till 2 semitone difference and there were no significant changes in the sensitivity further.

3.1.3. Sequential information transfer analysis

A sequential information transfer analysis [21] was performed on group data for each experimental condition to assess the amount of information transfer from stimulus to response for a set of phonetic feature. This was done with 'Feature Information Xfer (FIX)' software from the Department of Linguistics, University College of London. Sequential Information Transfer Analysis (SINFA) is a method for determining the degree of information transfer from stimulus to response that is attributable to a particular feature. First, each feature's information transfer from

Table X. Features assigned to different vowels.

	e	i	o	u
Place	F	F	B	B
Lip rounding	-	-	+	+
Height	-	+	-	+

Table XI. Relative information transfer in normal hearing listeners. P/lr: Place/lip rounding; H: Height; Tit: Total information transferred.

	P/lr	H	Tit
0 semitone difference	0.14	0.23	0.5
1 semitone difference	0.4	0.4	0.9
2 semitone difference	0.6	0.6	1.2
4 semitone difference	0.5	0.5	1.14

Table XII. Relative information transfer in cochlear hearing loss group. P/lr: Place/lip rounding; H: Height; Tit: Total information transferred.

	P/lr	H	Tit
0 semitone difference	0.009	0.02	0.05
1 semitone difference	0.04	0.01	0.07
2 semitone difference	0.04	0.02	0.07
4 semitone difference	0.06	0.03	0.12

stimulus to response is computed. Then a sequence of iterations is done in which one feature selected according to some criteria is partialled out per iteration by holding it constant. Typically, the feature that is transmitted to the maximum extent is held constant in subsequent iterations. Table 10 shows the different features that were assigned to vowels. The vowels were classified based on the features of tongue height, lip rounding and place of articulation. Thus the vowels were either front or back (place), and rounded or unrounded (lip rounding) and high or low (height).

Table XI shows the relative information transmitted in bits per stimulus for each feature. Place and the lip rounding features were equivalent in the vowels used and hence are not shown separately. Table XII depicts the same information in cochlear hearing loss group.

The numbers in the 2nd and the 3rd columns represent the extent of information transmitted. 0 indicates no transmission of that particular feature and a value of '1' indicates maximum transmission of information. The numbers in the fourth column represent the total information transmitted. Total information that can be transmitted for 4 stimuli is 2 bits. In general, the pattern of information transfer as shown by SINFA analysis was similar to the pattern found in the confusion matrices (Tables II–IX). As the differences in pitch between target and reference vowels increased feature information transmitted improved in normal hearing listeners. But in hearing impaired group this improvement was seen only when the pitch difference was four semitones.

Table XIII. Average speech identification scores (in %) in normal hearing and cochlear hearing loss group. Values in parenthesis indicates one standard deviation. Nhg: Normal hearing group, Chlg: Cochlear hearing loss group.

	20 dB SNR	15 dB SNR	10 dB SNR	5 dB SNR	0 dB SNR	-5 dB SNR	-10 dB SNR
Nhg	100 (0)	100 (0)	100 (0)	100 (0)	94.34 (0.7)	13.04 (0.8)	0 (0)
Chlg	98.57 (0.37)	97.14 (0.6)	92.14 (1.2)	33.92857 (1.3)	0.357 (0.09)	0 (0)	0 (0)

Table XIV. Mean and standard deviation of SNR-50 values in both the groups. Chlg: Cochlear hearing loss group, Nhg: Normal hearing group.

	Chlg	Nhg
Mean SNR-50	6.3	-2.8
One standard deviation	2.9	1.2

3.2. Speech perception in noise

Table XIII shows average speech identification scores and standard deviation obtained at different SNRs in normal hearing group and cochlear hearing loss. From Table XIII it can be seen that speech identification scores were poorer in cochlear hearing loss group compared to normal hearing group.

From the above data threshold SNR required to obtain the 50% speech identification scores were calculated using Spearman and Karber equation [22],

$$50\% = i + \frac{1}{2}(d) - (d)(\#correct)/(w),$$

where i = the initial presentation level (dB S/N), d = the attenuation step size (decrement), w = the number of items per decrement.

Table XIV shows mean and standard deviation of SNR-50 values in both the groups. From the Table XIV it is evident that SNR-50 scores of cochlear hearing loss groups was poorer than normal hearing group. Independent samples t test showed that SNR-50 mean SNR-50 was significantly better in normal hearing group compared to cochlear hearing loss group ($t=14.24$, $p<0.05$).

3.3. Relationship between concurrent vowel identification scores and speech perception in noise

To find the relationship between concurrent vowel identification measures and speech perception a series of correlation analysis were performed with concurrent vowel identification as independent variable and SNR-50 as dependent variable. Correlation coefficients were also calculated between the amount of improvement in vowel identification scores with the F0 disparities and SNR-50. For this purpose difference in the vowel identification scores between 0 semitone difference condition and one, two and four semitone difference conditions were calculated. Combined data of normal hearing and hearing impaired individuals were used to calculate correlation coefficients. Table 13 shows correlation coefficients between SNR-50 and concurrent vowel identification measures.

From Table XV it is clear that SNR-50 was significantly correlated with concurrent vowel identification as well as improvement in vowel identification with the F0 disparity. Negative correlations between concurrent vowel identification measures and SNR-50 indicate that individuals who had better concurrent vowel identification scores were able to identify the 50% of the speech presented at much lower (worse) SNRs.

4. Discussion

Results of the present study showed that individuals with cochlear hearing loss had poorer ability to segregate two vowels using F0 cues compared to normal hearing group. Hearing impaired individuals were poor in identifying the two vowels especially in 0 semitone difference condition. Similar results have been obtained by previous investigators too [23]. In the present study concurrent vowel identification and speech perception in noise testing was carried out at MCL without providing frequency specific gain for individuals with cochlear hearing loss. However, it is unlikely that the observed results could be due to reduced audibility because a) speech identification scores in quiet was good and was not significantly different between normal hearing and individuals with hearing impairment b) the observed differential effect of change in semitone on normal hearing and individuals with hearing impairment cannot be explained by reduced audibility only. To understand the effect of cochlear hearing status on concurrent vowel identification, physiological mechanism behind concurrent vowel identification should be known. Various models have been proposed to explain the physiological mechanism behind concurrent vowel identification. In these models either spectral information or temporal information or both are used to match the most appropriate template corresponds to the presented vowels. These models can be categorized into three categories (i) spectral models (ii) temporal cues and (iii) spectro-temporal models. According to these models

Spectral model assumes that the outputs of the auditory filters were analyzed to identify the fundamental (f0) or fundamentals which might result in the pattern of peaks and valleys in the excitation spectrum. Low frequency peaks in the excitation spectrum are assumed resolved harmonics of one or both of the two 'f0's. These harmonics are assigned to one or both groups and two new spectral profiles are reconstructed from two sets of spectral peaks. Then formant frequencies for each reconstructed spectral profile are extracted and based on this both the vowels are identified [17].

Table XV. Correlation coefficients between SNR-50 and other psychophysical measures. **: $p < 0.01$. CVI-0 = concurrent vowel identification without any pitch difference, CVI-1 = concurrent vowel identification with one semitone pitch difference, CVI-2 = concurrent vowel identification with two semitone pitch difference, CVI-4 = concurrent vowel identification with four semitone pitch difference, CVI1-CVI0 = concurrent vowel identification with one semitone pitch difference minus concurrent vowel identification without any pitch difference, CVI2-CVI0 = concurrent vowel identification with two semitone pitch difference minus concurrent vowel identification without any pitch difference, CVI4-CVI0 = concurrent vowel identification with four semitone pitch difference minus concurrent vowel identification without any pitch difference.

SNR-50	CVI-0	CVI-1	CVI-2	CVI-4	CVI1-CVI0	CVI2-CVI0	CVI4-CVI0
	-0.57**	-0.8**	-0.9**	-0.8**	-0.4**	-0.6**	-0.5**

Temporal models proposed by de Cheveigne [15] works on a principle of neural cancellation. Auditory nerve discharges for a given vowel are grouped together according to the delay pattern that corresponds to the period of the vowel's F0. Neural cancellation operates on series of delay circuits, where a delay equal to the period of the F0 was added so that input spikes coinciding with delayed spikes are canceled in that specific delay circuit. For concurrently presented vowels, one vowel is cancelled in one delay circuit and another vowel is cancelled in different delay circuit. Finally, auditory channels contributing to each of the vowels are selected by matching to the template.

Spectro-temporal model of concurrent vowel identification was proposed by Meddis and Hewitt [24]. According to this model, concurrently presented vowels are divided into series of band passed signal at peripheral auditory filters. A running autocorrelation functions (ACF) are calculated in each band passed signals and then pooled ACF was obtained by summing the ACFs across the auditory filters. F0 was estimated using the peaks in the pooled ACF and with the help of the estimated F0, information in the different auditory filters is segregated into two mutually exclusive subsets. Finally, both the vowels are identified by applying a template-matching procedure to the pooled ACF of each subset.

From the above mentioned models it is clear that changes in the auditory filtering and/or neural phase locking could influence concurrent vowel identification. In concurrently presented vowels, perception of one vowel might dominate the other vowel due to the relative intensity and the frequency of the formant peaks. Normal hearing Individuals with intact auditory filters is able to overcome the dominance effect. However, individuals with cochlear hearing loss are unable to overcome this dominance effect due to increased spread masking as a result of broadened auditory filters [23]. Poor resolving of lower harmonics due to broad auditory filters could be possibly contributing for poor concurrent sound identification [25, 26]. Few observations indicated that cochlear hearing loss can lead to reduced precision in phase locking for formant peaks [27]. Poor phase locking might influence neural cancellation or ACF which might results in an output that is different from the actual template. In normal hearing listeners as the F0 differences between the concurrent vowels increased perception of both the place and tongue height information increased. In cochlear hearing loss group with the increase in the F0 difference perception

Table XVI. ID: Subject ID; Sis: Speech identification scores (in quiet); Pta: Pure tone average; Coa: Configuration of audiogram.

ID	Age	Sis	Pta	Coa
E1	40	88	50	Flat
E2	40	90	52.5	Rising
E3	45	90	33.75	Sloping
E4	56	88	57.5	Flat
E5	44	100	53.75	Flat
E6	36	100	47.5	Flat
E9	47	90	52.5	Sloping
E10	56	92	36.25	Rising
E15	55	86	55	Sloping
E16	40	86	41.25	Flat
E17	45	90	33.75	Sloping
E18	64	92	41.25	Sloping
E21	55	86	56.25	Sloping
E24	40	100	48.75	Rising

of place feature increased marginally, but not the tongue height feature. This lack of improvement in vowel identification scores upon increase in the difference between F0 of concurrent vowels indicates inability of hearing impaired listeners to use the F0 cues in stream segregation. On the other hand normal listeners can derive significant benefits when the F0 of concurrent vowels were varied.

Inability of hearing impaired listeners to use F0 frequency cues in stream segregation may pose difficulty in understanding speech especially, when the competing signal is speech itself. This was reflected in speech perception in noise assessment where cochlear hearing loss group required higher SNR to perceive 50% of the speech presented. Average SNR-50 of cochlear hearing loss group was approximately 3 times more than normal hearing group. Significant high negative correlations (-0.5 to -0.9) indicate that individuals who had better concurrent vowel identification scores also had better SNR-50. This result shows that stream segregation capabilities based on F0 is crucial for speech understanding in noise especially when the competing signal is speech itself. These results show that differences in the F0 are one of the most robust cues for stream segregation.

5. Conclusions

Results of the present study showed that stream segregation capabilities based on F0 cues in individuals with

cochlear hearing is poorer than normal hearing listeners. Significant correlations between concurrent vowel identification scores and SNR-50 indicate that differences in the F0 are one of the most robust cues for stream segregation.

References

- [1] B. C. Moore: Cochlear hearing loss: physiological, psychological and technical issues (2nd ed.). John Wiley & Sons Ltd., West Sussex, 2007.
- [2] P. N. Kulkarni, P. C. Pandey, D. S. Jangamashetty: Multi-band frequency compression for reducing the effects of spectral masking. *International Journal of Speech Technology* **10** (2009) 219–227.
- [3] J. R. Dubno, D. D. Dirks, A. B. Schaefer: Effects of hearing loss on utilization of short-duration spectral cues in stop consonant recognition. *Journal of the Acoustical Society of America* **81** (1987) 1940–1947.
- [4] C. W. Turner, D. A. Fabry, S. Barrett, A. R. Horwitz: Detection and recognition of stop consonants by normal-hearing and hearing-impaired listeners. *Journal of Speech and Hearing Research* **35** (1992) 942–949.
- [5] S. A. Phatak, Y. S. Yoon, D. M. Gooler, J. B. Allen: Consonant recognition loss in hearing impaired listeners. *Journal of the Acoustical Society of America* **126** (2009) 2683–2694.
- [6] S. L. Phillips, S. J. Ritcher, D. McPherson: Voiced initial consonant perception deficits in older listners with hearing loss and good and poor word recognition. *Journal of Speech, Language, and Hearing research* **52** (2009) 118–129.
- [7] K. Hopkins, B. C. Moore, M. A. Stone: Effects of moderate cochlear hearing loss on the ability to benefit from temporal fine structure information in speech. *Journal of the Acoustical Society of America* **123** (2008) 1140–1153.
- [8] A. J. Oxenham, B. C. J. Moore: Modeling the effects of peripheral nonlinearity in normal and impaired hearing. – In: *Modeling Sensorineural Hearing Loss*. W. Jesteadt (ed.). Erlbaum, Hillsdale, NJ, 1997.
- [9] O. Strelcyk, T. Dau: Relations between frequency selectivity, temporal fine-structure processing, and speech reception in impaired hearing. *The Journal of the Acoustical Society of America* **125** (2009) 3328–3345.
- [10] T. Vongpaisal, M. K. Pichora-Fuller: Effect of age on F0 difference limen and concurrent vowel identification. *Journal of Speech, Language and Hearing Research* **50** (2007) 1139–1156.
- [11] A. S. Bregman: Auditory scene analysis: The perceptual organization of sound. MIT Press, Cambridge, 1990.
- [12] C. J. Darwin, R. P. Carlyon: Auditory grouping. – In: *Hearing*. B. C. Moore (ed.). Academic Press, San Diego: CA, 1995.
- [13] D. Fogerty, D. Kewley-Port, L. E. Humes: Asynchronous vowel-pair identification across the adult life span for monaural and dichotic presentations. *Journal of Speech, Language and Hearing Research* **55** (2012) 487–499.
- [14] K. H. Arehart, P. E. Souza, R. K. Muralimanohar, C. W. Miller: Effects of age on concurrent vowel perception in acoustic and simulated electroacoustic hearing. *Journal of Speech, Language and Hearing Research* **54** (2011) 190–210.
- [15] A. de Cheveigne: Waveform interactions and the segregation of concurrent vowels. *Journal of the Acoustical Society of America* **106** (1997) 2959–2972.
- [16] K. H. Arehart, J. Rossi-Katz, J. Swensson-Prutsmann: Double-vowel perception in listeners with cochlear hearing loss: differences in fundamental frequency, ear of presentation, and relative amplitude. *J. Speech Lang. Hear. Res.* **48** (2005) 236–252.
- [17] P. F. Assmann, Q. Summerfield: Modeling the perception of concurrent vowels: Vowels with the same fundamental frequency. *Journal of the Acoustical Society of America* (1989) 327–338.
- [18] R. Methi, Avinash, U. A. Kumar: Development of sentence-material for quick speech in noise test (Quick SIN) in Kannada. *Journal of the Indian Speech and Hearing Association* **23** (2009) 59–65.
- [19] J. Hillenbrand, L. A. Getty, M. J. Clark, K. Wheeler: Acoustic characteristics of American English vowels. *Journal of the Acoustical Society of America* **97** (1995) 3099–3111.
- [20] T. Francart, A. van Wieringen, J. Wouters: APEX 3: A multi-purpose test platform for auditory psychophysical experiments. *Journal of Neuroscience methods* **172** (2008) 283–293.
- [21] M. D. Wang, R. C. Bilger: Consonant confusions in noise: a study of perceptual features. *Journal of the Acoustical Society of America* **54** (1973) 1248–1266.
- [22] D. J. Finney: Statistical method in biological assay. C. Griffin, London, 1952.
- [23] K. H. Arehart, J. Rossi-Katz, J. Swensson-Prutaman: Double-vowel perception in listeners with cochlear hearing loss: differences in fundamental frequency, ear of presentation, and relative amplitude. *Journal of Speech, Language and Hearing Research* **48** (2005) 236–252.
- [24] R. Meddis, M. J. Hewitt: Modeling the identification of concurrent vowels with different fundamental frequencies. *Journal of the Acoustical Society of America* **91** (1992) 233–245.
- [25] G. Gilbert, C. Micheyl: Influence of competing multi-talker babble on frequency importance functions for speech measured using a correlational approach. *Acta Acustica united with Acustica* **91** (2005) 145–154.
- [26] M. K. Qin, A. J. Oxenham: Effects of simulated cochlear-implant processing on speech reception in fluctuating maskers. *Journal of the Acoustical Society of America* **114** (2003) 446–454.
- [27] R. L. Miller, J. R. Schilling, K. R. Frank, E. D. Young: Effects of acoustical trauma on the representation of the vowel "eh" in cat auditory nerve fibres. *Journal of the Acoustical Society of America* **101** (1997) 3602–3016.
- [28] P. F. Assmann, Q. Summerfield: Modelling of the perception of concurrent vowels: Vowels with different fundamental frequencies. *Journal of the Acoustical Society of America* **88** (1990) 680–697.