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Original Article

The Relationship between Temporal Integration and Temporal Envelope Perception in Noise by Males with Mild Sensorineural Hearing Loss

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OBJECTIVES: A surge of literature indicated that temporal integration and temporal envelope perception contribute largely to the perception of speech. A review of literature showed that the perception of speech with temporal integration and temporal envelope perception in noise might be affected due to sensorineural hearing loss but to a varying degree. Because the temporal integration and temporal envelope share similar physiological processing at the cochlear level, the present study was aimed to identify the relationship between temporal integration and temporal envelope perception in noise by individuals with mild sensorineural hearing loss.

MATERIALS and METHODS: Thirty adult males with mild sensorineural hearing loss and thirty age- and gender-matched normal-hearing individuals volunteered for being the participants of the study. The temporal integration was measured using synthetic consonant–vowel–consonant syllables, varied for onset, offset, and onset–offset of second and third formant frequencies of the vowel following and preceding consonants in six equal steps, thus forming a six-step onset, offset, and onset–offset continuum, each. The duration of the transition was kept short (40 ms) in one set of continua and long (80 ms) in another. Temporal integration scores were calculated as the differences in the identification of the categorical boundary between short- and long-transition continua. Temporal envelope perception was measured using sentences processed in quiet, 0 dB, and -5 dB signal-to-noise ratios at 4, 8, 16, and 32 contemporary frequency channels, and the temporal envelope was extracted for each sentence using the Hilbert transformation.

RESULTS: A significant effect of hearing loss was observed on temporal integration, but not on temporal envelope perception. However, when the temporal integration abilities were controlled, the variable effect of hearing loss on temporal envelope perception was noted.

CONCLUSION: It was important to measure the temporal integration to accurately account for the envelope perception by individuals with normal hearing and those with hearing loss.

KEYWORDS: Auditory processing, psychoacoustics, hearing loss, temporal processing, speech perception

INTRODUCTION

The temporal envelope is defined as the amplitude contour of a signal that changes over time [1, 2]. Hilbert defined temporal envelopes of a signal as the amplitude contours of a sound in a narrow frequency range [3]. Speech is a broad frequency signal. When speech is processed in the cochlea, it passes through a series of band-pass filters [4] known as the auditory filters. Each filter allows only a specific frequency of the speech signal to pass through it, which results in the decomposition of broad frequency speech signals into a series of narrow frequency signals. The amplitude contours of these narrow frequency signals are the envelope of the speech [3]. Thus, the cochlea converts the broad frequency speech into its envelope for further processing. Ziegler and Goswami [5] have found that the amplitude envelopes are essential for segmenting the speech signals into smaller units and they help in perceiving the prosody to mark the sentences, words, and syllable boundaries.

Studies have shown that the addition of noise to speech deteriorates the speech intelligibility. In such situations, it is essential to note the relative contribution of the temporal envelope in the perception of speech in noise. Apoux et al. [6] have investigated the

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contribution of the temporal envelope in the perception of speech in noise. Their findings revealed that when the envelope cues in the speech were masked, the perception of speech was severely affected. Their observations suggested that the identification of speech sounds extensively relies on the temporal envelope cues, even in the presence of noise.

Turner et al. [7] have controlled the spectral features of the signal to investigate the role of the temporal envelope in the perception of speech in individuals with hearing loss. According to them, the perception of speech with temporal envelope was minimally affected due to the cochlear hearing loss. Lorenzi et al. [8] and Bacon and Gleitman [9] have also reported that the individuals with hearing loss performed like normal-hearing individuals in detecting the amplitude modulations in the signal. However, when Henry et al. [10] assessed the effect of noise-induced hearing loss on the tonotopic coding of temporal envelope and temporal fine structures, they found that the envelope coding becomes non-tonotopic as the cochlear damage increased. The researchers concluded that the broadening of the auditory filters due to the cochlear damage shifted the characteristic frequency of that auditory filter, which resulted in the disruption of the envelope tonotopicity. The problem was more pronounced in the presence of noise, where the noise masked the redundant acoustic cues in the signal, and the perception of speech solely relied on the temporal envelope cues.

Lorenzi et al. [11] had investigated the ability of the individuals with hearing loss to reconstruct the temporal envelopes in the speech, and found that noise degrades the amplitude modulation cues in the speech. In such situations, the normal-hearing listeners retrieve the information that was lost due to the distorted amplitude modulation of the signal, from the frequency modulated speech cues present in that signal. However, in individuals with cochlear hearing loss, the broadening of the auditory filters resulted in the inability to retrieve the envelope information from the frequency modulation cues. These research findings were in contrast with the findings of other researchers. It was thus important to identify the factors responsible for the difference in the findings of the temporal envelope perception in noise by individuals with normal hearing and those with mild sensorineural hearing loss.

The auditory system has limited capacity to follow the time-varying envelope, known as the temporal resolution of the auditory system. There are various factors that contribute to the perception of speech with temporal envelope. One such factor is the ability of the individual to summate/integrate the acoustic energy over time, which is known as the auditory temporal integration [12]. When the cochlea receives an acoustic stimulus, the basilar membrane is activated, followed by an exponential decay. The rate of decay is characterized by a time constant, measured in terms of the length of the temporal window, i.e., the temporal integration ability of the auditory system [13]. In the perception of speech, consonants are characterized by rapid spectral changes and use the short temporal window, whereas vowels use a long temporal window [14, 15]. When the speech signal is processed through narrow band auditory filters, the identification of speech is dependent upon the number of auditory filters activated at a time and the rate at which the filter peak decays to avoid the splatter of energy to the adjacent filters. Because the decay in the peak of the auditory filter is measured as the temporal integration, the temporal integration and the envelope perception share similar physiological processing at the cochlear level. It was hence reasonable to assume that the temporal integration abilities and temporal envelope perception are related to each other.

Thus, the present study was aimed to identify the role of temporal integration and temporal envelope in the perception of speech and the relationship between these two processes in individuals with normal hearing and those with mild cochlear hearing loss.

MATERIALS AND METHODS

Participants

Sixty adult males within the age range of 30-40 years volunteered for the study. Male participants were selected as it was reported that gender is an influencing factor in the perception of speech, and males perceive speech better in noisy situations [16]. Among them, 30 participants were diagnosed as having mild sensorineural hearing loss in both ears [Pure Tone Average (PTA) between 26-40 dB; Speech Recognition Thresholds (SRT) within 10 dB of PTA; Speech Identification Scores (SIS) of greater than 90%; Air-Bone Gap (ABG) equal to or less than 10 dB] [17]. The audiogram configuration was flat or sloping (not precipitously or steeply sloping) for all the participants. Among the participants with hearing loss, 23/30 had developed hearing loss due to occupational noise exposure, 4/30 had hearing loss secondary to ototoxicity, 1/30 participant had diabetes mellitus type 2, which may account for his reduced hearing sensitivity, and the remaining 2/30 participants had hearing loss with no apparent cause. The selection of the number of participants was based on the statistical power analysis depending upon their inclusion criterion, derived from the population sample at a 95% confidence interval and 5% error rate. The ideal sample size needed for the present study was 27 individuals with hearing loss. The participants in the control group (n=30) had normal hearing sensitivity (PTA≤15 dB; SRT±10 dB of PTA; SIS≥90%) [17] and did not had any past complaint of hearing loss or related pathology. Written informed consent was obtained from participants, and appropriate permission was taken from the institutional ethical board.

Test Stimuli

The stimuli for temporal integration were synthesized consonant–vowel–consonant (CVC) syllable (\bΛb\) generated using the Klatt parallel/cascade synthesizer [18] implemented in Matlab software (The Mathwork Inc., Natick, MA, USA) [19]. The onsets of second and third formant frequencies (F2 and F3, respectively) after the first \b\, i.e., before the vowel \Λ\, in the \bΛb\ syllable, were increased from 1100 to 1600 Hz and from 2100 to 2600 Hz, respectively, in five equal-steps of 100 Hz each. The onsets of F2 and F3 formant frequencies of 1600 Hz and 2600 Hz, respectively, are the same as that of CV \dΛ\. Thus, a six-step continuum (original syllable and five-step modifications of the onsets of F2 and F3) from \bΛb\ at one end to \dΛb\ at another end was created. This was labeled as the 'onset continuum.' Similarly, in another \bΛb\ syllable, the offset of F2-F3 formant frequencies before the last \b\, i.e., after the vowel \Λ\ was increased from 1100 Hz to 1600 Hz (F2) and 2100 Hz to 2600 Hz (F3), to generate a six-step 'offset continuum' from \bΛb\ to \bΛd\. Finally, both the onset and offset of F2-F3 after the first \b\ and before the last \b\, in the \

bΛb\ syllable, were increased from 1100 Hz to 1600 Hz (F2) and from 2100 Hz to 2600 Hz (F3) to generate six-step 'onset–offset \bΛb\ to \dΛd\ continua'. The formant transition durations (\b\-\Λ\ and \Λ\-\b\) in these three continua were kept at 40 ms, and these continua were labeled as short-transition continua. Another set of three continua, exactly the same as short-transition continua, were generated, but the formant transition duration (\b\-\Λ\ and \Λ\-\b\) in each stimulus of the continua was kept as 80 ms. These continua with 80 ms transition durations were labeled as long-transition continua. Thus, totally, six continua were generated and saved for further use.

Temporal envelope perception was measured for 12 lists (10 sentences/list) of standard Kannada sentences [20]. Each sentence consisted of four bisyllabic words. Speech-shaped noise corresponding to each sentence was generated using Matlab and added to four lists of relevant sentences at 0 dB signal-to-noise ratio (SNR) and to four lists at -5 dB SNR, whereas the remaining four lists were kept at quiet condition, using Matlab. All the sentences were then filtered through a sixth-order Butterworth filter and processed in 4, 8, 16, and 32 channels based on Greenwood function, [21] such that each list in each SNR level was filtered for the specific number of channels. Hence, each of the 12 lists was different regarding its SNR level and/or the number of channels or both. The envelope for each sentence in all the lists was extracted using a custom Matlab code based on the Hilbert transformation. The sentence signal was converted into an analytic signal, and the amplitude and frequency of the signal were modulated. The envelope was computed by removing the center frequency of the sub-band signal and limiting the range and rate of frequency modulation while retaining the amplitude envelope of the signal. The resultant 12 lists of sentences with envelope only information were saved on the computer for further use.

Procedure

The stimuli for temporal integration, i.e., six continua (six-stimuli/continuum; each stimulus for five-times, i.e., five-trials) were presented using "ExperimentMFC" extension of Praat software (University of Amsterdam, Amsterdam, The Netherlands) [22]. Thus, totally, 180 stimuli were presented auditorily, one by one, to each participant, and the responses were recorded in a four-alternative forced choice paradigm. The participants were shown four syllables, viz. \bΛb\, \dΛb\, \bΛd\, and \dΛd\, each written in Kannada script in the four quarters of the computer screen (15.8 inches). They were instructed to point to the syllable on the screen as they heard, and the same was clicked by the experimenter. The responses of each participant for each continuum, and each trial were saved in the computer for further analysis.

The recorded 12 lists of sentences with temporal envelope information, each at different SNR levels and processed through different frequency channels, were presented to the participants using Alvin software (Western Michigan University, Kalamazoo, MI, USA) [23]. The Alvin program is designed to control the stimulus presentation and collect the participants' responses for behavioral research. The sentences presented, one by one, through Alvin were randomized (using a simple randomization technique) across the SNR levels and number of frequency channels. The participants were instructed to repeat the sentences as they heard. The participants' responses were recorded using the Alvin software and stored on the computer for further analysis.

The stimuli for both temporal integration and temporal envelope perception were presented binaurally at each participant's most comfortable loudness level, using the personal computer (Dell Inspiron 15R SE), routed via the calibrated audiometer (Invetis Piano; Inventis Audiology Equipment, Padova, Italy) through TDH-39 (Telephonics, Farmingdale, NY, USA) circumaural headphones in an acoustically treated room [24].

Scoring

Temporal integration was measured in terms of the identification of either syllable at the categorical boundary and the width of the categorical boundary. The categorical boundary was defined as the point along the continua where the perception shifted from one end to another at least 50% of times [25]. The width of the boundary was calculated as the distance between 25^{th} and 75^{th} percentage points, [26], i.e., the difference in the values when the perception shifted from one end to another was at least 75% of times and 25% of times. The categorical boundary was calculated for each of the six continua for the last three trials, separately, for each participant. The first two trials were considered as the practice trials, and the categorical boundary for them was not calculated.

The recorded responses for the envelope-processed sentences were analyzed as the number of words repeated per sentence. Each correctly repeated word in a sentence was given a score of "1", whereas a partially correct word repeated by the participant was scored as "0.5". The incorrectly repeated/not repeated words were scored as "0". Thus, for each sentence, a minimum score of "0" or a maximum score of "4" was possibly given.

Statistical Analysis

The trial-to-trial consistency of the responses for temporal integration was measured using repeated measures analysis of variance (ANOVA). The categorical boundary and categorical width for temporal integration were measured using logistic regression with linear/non-linear interpolation. A paired sample *t*-test compared the categorical boundary and categorical width across short and long transitions, between individuals with normal hearing and those with hearing loss. The envelope perception across different SNR levels, number of channels, and groups werecompared using univariate ANOVA. The entire statistical analysis was carried out using Statistical Package for Social Science (SPSS) software ver., 23 (IBM Corp.; Armonk, NY, USA).

RESULTS

The data were normally distributed across groups (Shapiro–Wilk test, $p>0.05$) for the scores of temporal integration and temporal envelope perception. There was no significant difference in the scores of each trial for temporal integration [$F(2, 1910)=1.002$; $p=0.367$], indicating that the responses were consistent across trials. The variability in the responses was measured by comparing the standard deviation from trial to trial for short- and long-transition durations, and individuals with normal hearing and those with hearing loss. The variability was significantly higher for short transition [$F(2, 1910)=4.16$; $p=0.002$] and for individuals with hearing loss [$F(1, 1910)=3.89$; $p=0.0001$]. Bonferroni's multiple pairwise comparisons revealed that individuals with hearing loss had high variability for both short and long transitions, whereas normal-hearing individuals had significant variability for short-transition continua but not for long-transition continua.

The results of the categorical boundary for temporal integration, as tabulated in Table 1, revealed that there was no significant effect of transition duration on the perception of speech with temporal integration across the three (onset, offset, and onset–offset) continua for both normal individuals and those with hearing loss. The only exception to these results was the significant effect of transition duration for categorical width in the offset continuum, for individuals with hearing loss. On the other hand, there was a significant effect of hearing loss on the categorical perception of CVC syllables, irrespective of the transition duration.

The scores obtained in the temporal envelope perception experiment for the correct identification of the words were averaged for all the ten sentences in a list and were considered as the dependent variables. The SNR levels, the number of channels, and the group distribution were independent variables. The results are tabulated in Table 2, which revealed a significant effect of SNR levels and number of channels on sentence perception with temporal envelopes. The interactions between group and SNR, SNR and channel, and among the group, SNR, and channel were also statistically significant. The perception of sentences improved with increasing SNR levels. The perception of sentences was also found to be better when the sentences were processed through higher number of channels, especially 16 and 32 channels. The pairwise comparison revealed no significant difference in the sentence perception with temporal envelopes between 16 channels and 32 channels conditions. Further, no statistically significant effect of group and interaction effect between group and channel on sentence perception with temporal envelopes were noted. These results were in contrast with the findings of the temporal integration, where a significant effect of hearing loss was observed.

The relationship between temporal integration and temporal envelope perception was further determined. Based on the temporal integration data, the participants with hearing loss were divided into two groups, one having good temporal integration abilities in terms of relatively narrower categorical boundary and less variability among trials and other with poor temporal integration abilities. The cut-off was taken as the median point. When the envelope perception was compared between individuals having good and poor temporal integration abilities, a significant difference in the envelope perception was noted ($F=128.78$; $p<0.05$). The individuals with poorer temporal integration abilities were also having significantly poorer envelope perception abilities than normal-hearing individuals ($F=144.71$;

Table 1. The results of a paired sample t-test showing the t-values and p-values at the categorical boundary and categorical width for comparisons across the transition durations and group

	Categorical boundary		Categorical width		Categorical boundary		Categorical width	
	t-values	p	*t*-values	p	*t*-values	p	*t*-values	p
	Normal individuals				Individuals with hearing loss			
STD[a] vs. LTD[b] @ onset	1.943	0.062	0.745	0.463	0.776	0.444	0.291	0.773
STD vs. LTD @ offset	1.159	0.256	0.510	0.614	1.203	0.239	2.490	0.019*
STD vs. LTD @ onset–offset	0.984	0.333	1.044	0.305	1.472	0.152	0.815	0.422
	STD				LTD			
Normal vs. H.L.[c] @ onset	2.523	0.005*	3.279	0.002*	2.076	0.042*	1.913	0.066
Normal vs. H.L. @ offset	4.232	0.001*	2.959	0.034*	2.117	0.027*	2.681	0.041*
Normal vs. H.L. @ onset–offset	2.297	0.049*	2.365	0.003*	2.410	0.023*	4.610	0.005*

*Significant at 95% confidence interval.
[a]STD: Short-Transition Duration
[b]LTD: Long-Transition Duration
[c]H.L.: Hearing Loss

Table 2. The F-values and p-values for the main and the interaction effect of various independent variables (group, SNR, and number of channels) on the dependent variable (envelope perception scores) for sentence perception with temporal envelope

Source	dF	Mean square	F-values	p	Pη²
Group	1	275.963	4.948	>0.05	.611
SNRa	2	331.047	1313.509	<0.001*	.791
Channel	3	187.680	744.665	<0.001*	.762
Group * SNR	2	33.106	131.354	<0.001*	.274
Group * channel	3	9.441	7.459	>0.05	.139
SNR * channel	6	14.692	58.295	<0.001*	.334
Group * SNR * channel	6	18.255	72.431	<0.001*	.384

*Significant at 99.9% confidence interval.
[a]SNR: Signal-to-noise ratio

$p<0.05$); however, no such differences between individuals with hearing loss with good temporal integration abilities and normal-hearing individuals were noted.

DISCUSSION

The present study was designed to investigate the effect of hearing loss on the perception of speech with temporal envelope and temporal integration. The selection of participants was carefully designed where most of the intravenous variables like gender, the age of the participants, type and degree of hearing loss, audiometric configuration, hearing loss asymmetry, socio-economic status, and cultural background, etc. were controlled. The experiment designed for assessing the perception of speech with temporal integration used speech as stimuli, in contrast to most of the earlier studies on temporal integration, where pure tones were used [27]. Speech stimuli mimic closely to the real world listening and hence serve as better stimuli to assess the perception of speech [28]. However, the speech stimuli have seldom been used to assess the perception of speech using temporal integration, [29] probably due to difficulty in manipulating the acoustic and temporal characteristics of speech to make the stimuli suitable for assessing temporal integration. In the present study, synthesized CVC syllables were used as speech stimuli, where the acoustic and temporal parameters were easily manipulated. More than twenty acoustic parameters were considered to synthesize each stimulus so that it maximally represents natural-like speech. Care was taken to use the acoustic characteristics of the consonants and vowels in the CVC syllables like what was reported for the Kannada language [30, 31]. Three different CVC continua were selected to minimize the influence of neighboring spectral content on temporal integration. The stimuli presentation and response-recording paradigm were controlled and well established in the literature.

The stimuli used for assessing the perception of speech with temporal envelope were standardized Kannada sentences which were controlled based on linguistic variation, predictability, naturalness, and familiarity [20]. The envelope extraction method, i.e., the Hilbert transformation, is most common and well established in the literature [32, 33]. The responses were analyzed by three independent speech-language pathologists, who were also native Kannada speakers, to ensure inter-judge reliability. Overall, the methodology used in the present study was well controlled, and the responses were reliable. The results of the study revealed that hearing loss had a significant effect on the perception of speech with temporal integration but not with temporal envelope. These results are well established in the literature for temporal integration and temporal envelope perception.

However, Lorenzi et al. [11] have found that the cochlear hearing loss results in the broadening of the auditory filters and hence, results in the inability to utilize the envelope information in the speech. This finding was in contrast with others, and thus, it was thought to find the reason behind the difference in temporal envelope perception in noise by individuals with mild sensorineural hearing loss. Because temporal integration and temporal envelope perception share similar peripheral physiological processing, temporal integration abilities were assessed to account for the temporal envelope perception by individuals with hearing loss. The finding of the present study indicated a one-to-one relationship between temporal integration and envelope perception abilities. The individuals with good temporal integration abilities had normal-like temporal envelope perception, whereas those with poor temporal integration abilities had poor temporal envelope perception. It may hence be reasonable to state that the observed variability in envelope perception in the previous studies [16] may be attributed to deficits in temporal integration abilities.

CONCLUSION

The present study revealed that hearing loss affects temporal integration, but not temporal envelope perception. However, when temporal integration abilities were controlled, the variable effect of hearing loss on temporal envelope perception was noted. Thus, it is important to measure the temporal integration abilities to accurately account for the envelope perception by individuals with normal hearing and those with hearing loss.

Ethics Committee Approval: Ethic committee approval was received for this study from the Ethics Committee of JSS Institute of Speech and Hearing, Mysuru, India.

Informed Consent: Written informed consent was obtained from the patients who participated in this study.

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