Temporal Modulation Transfer Function Through Analog and Digital Hearing Aids

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Abstract

Temporal modulation transfer function (TMTF) is the representation of temporal resolution of the auditory system. Natural speech has amplitude variations in its envelope which needs to be properly decoded. Pathologies of cochlea as well as auditory nerve are reported to degrade the temporal resolution, in turn contributing to the poor speech perception observed in these individuals. Most of these individuals are rehabilitated through hearing aids for their reduced hearing sensitivity. Although there is a strong scientific evidence for improved hearing sensitivity with the hearing aids, just this may not be sufficient for perceiving all the cues of speech. An ideal aid should also efficiently enhance the temporal resolution which will result in better speech perception. Hence, the objectives of the study was to compare the TMTF between analog and digital hearing aids in normal hearing individuals as well as individuals with sensorineural hearing loss.A total of 21 adults were included in the study out of which 11 (20 ears) were individuals with sensorineural hearing loss (SNHL) and 10 (20 ears) were with normal hearing sensitivity. TMTF was estimated for 5 modulation frequencies; 8, 16, 32, 64, and 128 Hz, without and with hearing aids (analog and digital). The results showed reduced modulation sensitivity with the increase in modulation frequency in both the target groups and in all the experimental conditions. There was a significant difference between the TMTF of normal hearing individuals and individuals with SNHL and across 3 experimental conditions. The deficits in temporal resolution are attributed to the damage to the OHCs that leads to reduced frequency selectivity and broadening of the frequency tuning curves. The current hearing aids (analog and digital) distort the envelope of signal further adding to the already existing inherent distortions in the temporal resolutions in individuals with SNHL. Such distortions are higher in analog hearing aids. Hence, it is concluded that hearing aids with present technology does not fulfill all the requirements to enhance speech intelligibility to its best in individual with SNHL.

Key words: Temporal resolution, Modulation frequency, modulation threshold, temporal modulation transfer function

Natural speech is a complex signal which has variation in frequency and amplitude with respect to time. Every frequency band in speech can be considered to consist of a carrier signal (fine structure) and a time varying envelope. Envelope in turn contains many modulating frequencies, changing in amplitude which can be seen in temporal modulation spectrum. These variations contain the information that is essential for the identification of phonemes, syllables, words, and sentences. Dimitrijevic, Andrew, John, Picton & Terence (2004) reported the modulation properties of speech which is shown in Table l.

It is well known that auditory systems like all other sensory systems has limited temporal resolution and cannot follow temporal changes if the changes occur too rapidly (Viemeister,1979).

	Formant	Mean Frequency (Hz)	%AM
Vowels	F1	500	50
	F2	1500	34
	F3	2500	33
	F4	4000	21
Consonant-Vowels	F1	500	52
	F2	1500	51
	F3	2500	47
	F4	4000	50
Fricatives	F1	500	63
	F2	1500	57
	F3	2500	73
	F4	4000	34

Table 1: Frequency of AM for various speech sounds.

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Earlier investigations (Drullman, Festen & Plomp, 1994; Shanon, Zeng, Kamath, Wygonski, & Ekelid, 1995; Xu, Thompson & Pfingst, 2005) have demonstrated that consonant identification and sentence intelligibility could be achieved only if temporal modulation cues are as low as 50 Hz. Thus, any otological condition that restricts that temporal resolution below 50 Hz is expected to affect the perception of speech. Furthermore Drullman et al. (1994) reported that consonants, especially the stops suffer more from temporal smearing than vowels.

One such condition where the deficits in temporal resolution are frequently reported is cochlear pathology. Along with the reduction in hearing sensitivity, individuals with sensorineural hearing loss (SNHL), secondary to cochlear pathology possess deficit or reduction in temporal resolution **(**Hescot, Lorezi, Debruillex, & Camus, 2000), spectral resolution (Rawool, 2006) and speech perception in noise. These factors need to be considered during hearing aid trial for a successful fitting. Hence, it is important to determine whether hearing aids contribute in enhancing temporal resolution along with improving audibility.

Temporal resolution can be assessed through several methods like gap detection test (Forrest & Green, 1987, Samelli & Schochat, 2008, among others), speech perception in interrupted noise (Stuart, 2005) and temporal modulation transfer function (TMTF). However, the modulated signal used to estimate TMTF involves envelope, periodicity and fine structure, which in turn could help better in understanding the ability to perceive the amplitude variation of continuous speech.

Briefly, TMTF involves measurement of a ‘Modulation Transfer Function’ (MTF), an empirical function which measures the ability to follow or resolve sinusoidal amplitude modulation to the frequency of that modulation. The psychophysical measure of this function is the modulation threshold, and is usually defined as the depth of modulation necessary to just discriminate between a modulated and an unmodulated waveform as reported by Viemeister, (1979). Basically, MTF can be considered as a quantitative description of resolution. According to Drullman et al. (1994), perception of modulation varies with different modulation frequencies and lower modulation frequencies has its role in identification and higher modulation frequencies in discrimination of the signal

TMTF is reported to be abnormal in individuals with sensorineural hearing loss in most of the studies (Hescot et al., 2000; Bacon & Viemeister, 1985; Ajith & Jayaram, 2004). However, Moore, Glasberg and Bacon (1987) suggested that inherent fluctuations in amplitude of a stimulus are enhanced by recruitment along with the modulation being detected in individuals with cochlear hearing loss. They reported that listeners with cochlear hearing loss have normal temporal resolution, provided the signal is at comfortable levels. Hence, according to the results of Moore, Glasberg and Bacon, a hearing aid that compensates for the hearing sensitivity is sufficient to enhance the temporal resolution and in turn speech intelligibility. However, direct experimental evidence to this notion is not available. Hence, the primary purpose of the present study was to compare the TMTF with and without hearing aids at most comfortable levels of loudness. The second purpose was to compare TMTF between analog and digital hearing aids.

Objectives of the Study

The primary objective of the study was to compare the TMTF between analog and digital hearing aids. The secondary objective was to compare the TMTF between normal hearing individuals and individuals with sensorineural hearing loss, in unaided and aided conditions.

Method

Participants

Clinical Group

The experiment was conducted on 11 individuals with unilateral or bilateral sensorineural hearing loss. The participants of the study were tested monaurally and a total of 20 ears were tested. The participants were in the age range of 20 to 60 years. The hearing loss was either mild or moderate in its degree and was post lingual in its onset. The pattern of hearing loss was either flat across frequencies or gradually sloping from 250 Hz to 8000 Hz. Speech identification scores were obtained using Speech identification test in Kannada, developed and standardized by Vandana (1998). In all the individuals, the scores were proportional to the degree of hearing loss indicating that the hearing loss is predominantly due to cochlear pathology. Immittance evaluation showed type ‘A’ tympanogram with either presence or absence of acoustic reflexes. There was no past or present neurological dysfunction that was relevant to the present study.

Control Group

The experiment was also conducted on 10 individuals with normal hearing sensitivity who were matched for age with the participants in the clinical group. A total of 20 ears were tested. Unlike those in the clinical group, all the participants in the control group had normal hearing sensitivity (pure tone thresholds within 15 dB HL between 250 Hz and 8000 Hz) in both the ears. Participants had greater than 90% speech identification scores in quiet and did not have any significant difficulty in the speech perception in the presence of ipsilateral speech noise at 0dB signal to noise ratio. Immittance evaluation showed type ‘A’ tympanogram with the presence of acoustic reflexes. There was no past or present neurological dysfunction that was relevant to the study. An informed consent for participation in the study was obtained from all the participants.

Instrumentation

A computer with Daqgen software was used to generate the amplitude and frequency modulated signals. DaqGen is a stimulus signal generator portion of the upcoming Daqarta (Data AcQuisition and Real-Time Analysis) for Windows. This particular software was chosen because of 2 reasons: one, it allowed continuous signal generation with fine frequency resolution. Second, depth of modulation and the frequency of modulation could be independently controlled. A calibrated two channel *diagnostic audiometer (Orbiter-922) was* used to route the signals at uniform predefined levels and also to estimate the pure tone thresholds. A calibrated *immittance meter (Grason-stadler-TS)* was used to assess the middle ear status.

Test Stimuli

Amplitude and frequency modulated white noise was the test stimulus in the present experiment. The stimuli were generated online using Daqgen software. The software uses the following expression to modulate the signal: m(t) = [1 + m(sin2iifmt)]* n(t), where m = modulation index($0<m<1$): when m = 1, the wave is said to be 100% modulated. Fm = modulation frequency and n(t) = wide band noise. In the present study, the depth of modulation was varied in increments of 10% at 5 modulation frequencies: 8, 16, 32, 64 and 128 Hz. The modulation frequencies beyond 128 Hz were not used, as maximum modulation frequency in speech is within 128 Hz.

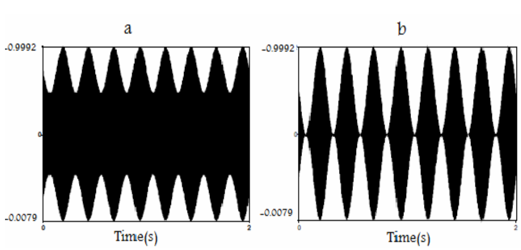

***Figure 1*:** Sinusoidally amplitude modulated white noise at 16 Hz, (a) 50% modulation depth (b) 100% modulation depth.

Test Procedure

Only those individuals who satisfied the subject selection criteria participated in the experiment. The actual test procedure involved estimation of modulation threshold. Modulation threshold was operationally defined as the lowest amplitude modulation depth at which modulation could be detected 75 % of the time. This way, modulation thresholds were estimated at different modulation frequencies, without and with hearing aids (analog & digital). The unaided modulation thresholds were determined, followed by the aided thresholds using analog and digital hearing aids. Both were moderate gain hearing aids. The analog hearing aid was a trimmer based aid while the digital hearing aid used in the study was a multi channel aid with WDRC and noise reduction algorithm features. Electroacoustic measurements were done to determine the category of hearing aids. NAL-NL1 was the prescription formula used in the digital hearing aid for providing appropriate gain. In normal hearing individuals, a gain of 5dB was given at all frequencies. Prior to the actual test procedure, participants were familiarized with amplitude modulated signals. Familiarization stimuli were modulated by 100% of the original amplitude. Unlike in earlier studies (Bacon & Viemeister, 1985, & Hescot et al.,2000), the present study used an identification task, as it was observed that alternative forced choice discrimination task was leading to high percentage of false positives. Continuous white noise without modulation was used only to create catch trials that could help in determining the reliability of the response in each individual.

Participants were instructed to indicate whether the stimulus was modulated or not modulated. Stimuli generated by Daqgen software were routed through the audiometer. Stimuli were presented through loudspeakers at most comfortable levels (MCLs). Although presenting the stimuli at equal SPLs would have been ideal, it was not practical when normal and hearing impaired groups were being compared. Hence, it was presented at MCLs. Across individuals with sensorineural hearing loss, MCL ranged between 80 and 90 dB HL in the unaided condition, and between 40 and 50 dB HL in the aided condition. Across normal hearing individuals, MCL ranged between 40 and 50 dB HL in the unaided condition, and between 20 and 30 dB HL in the aided condition. In order to obtain the ear specific response, the participants were instructed to occlude the non-test ear during the presentation of the stimuli. Each modulated signal was presented for a duration of 1 second.

The depth of modulation was varied randomly in 10 dB steps while estimating the thresholds. The modulation thresholds were estimated at modulation frequencies 8, 16, 32, 64, and 128 Hz. The raw data was in percentage which was later converted to dB by applying the following formula: Modulation threshold (dB) = 20 log (m/100), where 'm' refers to the modulation threshold in percentage.

Analysis

The modulation thresholds obtained across frequencies and across individuals were analysed to compare the TMTF between normal hearing individuals and individuals with sensorineural hearing loss, to compare the TMTF between aided and unaided conditions and, to compare TMTF between analog and digital hearing aids. The raw data was statistically compared using two-way ANOVA.

Results

In the present study, there were instances when the participants could not detect modulations even when the modulation depth was 100%. Such instances were seen only when the modulation frequencies were 32, 64 and 128 Hz but not in the lower modulation frequencies. The number of such ears was different across three conditions and between the two groups. The total number of ears in the control group that could not detect the modulations at 32, 64 and 128 Hz is graphically represented in Figure 2 (a). Similarly, the total number of ears with sensorineural hearing loss that could not detect the modulations is depicted in Figure 2(b). The following observations can be made from Figure 2 (a) and 2(b).

The number of ears where modulations could not be detected increased with increase in the modulation frequency. This was true in control as well as clinical group. The number of ears where modulations could not be detected also was more when the signal was routed through hearing aids compared to that in the unaided condition and, this trend was similar in both the groups. Furthermore, among the two hearing aids used in the study, the number of ears where modulations could not be detected was more when the signal was routed through analog hearing aid compared to digital hearing aid. Hence, data of these ears in those respective modulation frequencies and conditions were considered as missing data and the statistics done in the present study does not involve these data. The raw data was analyzed on two-way analysis of variance (ANOVA) to determine whether there is a significant effect of group and conditions on modulation thresholds. Two-way ANOVA was also used, to determine whether there is significant interactions between the effect of group and conditions.

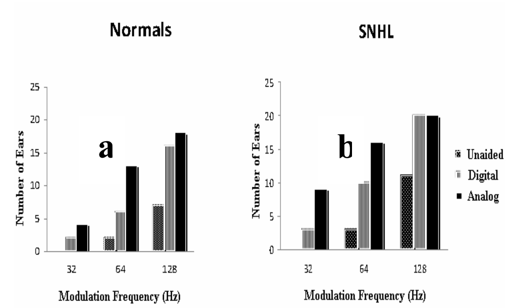

***Figure 2*:** Total number of ears in normal hearing individuals (IIa) and SNHL (IIb) groups, where modulations could not be detected even at 100 % modulation depth.

Effect of Group on TMTF

Table II shows the mean and standard deviation of modulation thresholds in control and sensorineural group in the five different modulation frequencies. The table also shows the F value and the degrees of freedom representing the significance of difference between the groups in terms of their modulation thresholds. Results of ANOVA showed a significant effect of group on modulation thresholds in 8, 16 and 32 Hz modulation frequencies while the mean differences are not significantly different in 64 and 128 Hz. Because the number of data available at 128 Hz were only 9 (in experimental group) and 13 (in control group) in the two groups, the results were cross checked on Mann-Whitney test. Results were same as that of ANOVA. Inspection of the means revealed that the participants in the control group had better modulation thresholds compared to participants with sensorineural hearing loss. Figure III shows the comparison of TMTF between control with clinical group across 3 experimental conditions ie., unaided (IIIa) digital (IIIb), analog (IIIc).

MF	Group	Mean	SD	F	(df)
8	Control	-4.06	1.12	22.73**	1(114)
	Exptal	-3.19	1.32		
16	Control	-3.71	1.03	45.18**	1(114)
	Expetal	-2.58	1.25		
32	Control	-2.98	1.25	22.17**	1(96)
	Exptal	-1.89	1.27		
64	Control	-1.61	1.27	2.87	1(64)
	Exptal	-1.03	1.04		
128	Control	-1.30	1.23	3.45	1(23)
	Exptal	-0.22	0.42		

Note: * * - p<0.01

Table 2: Means and standard deviation (SD) of modulation thresholds in control and clinical groups across five different modulation frequencies

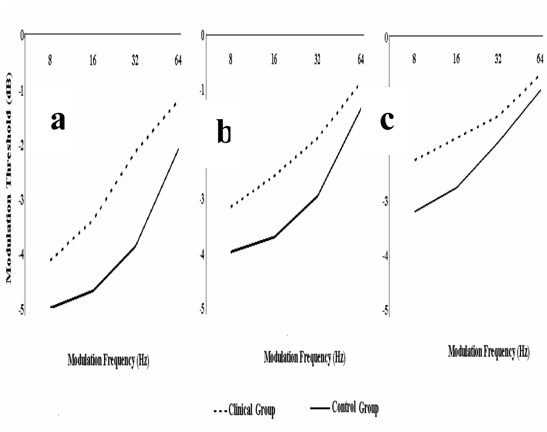

Figure 3: Comparison of TMTF between control and clinical group across 3 experimental conditions ie, unaided hearing aid (IIIa), digital hearing aid (IIIb) & analog hearing aid (IIIc).

MF	Condition	Mean (dB)	SD	F	df (error)
8 Hz	Unaided	-4.56	0.97	33.48**	2(114)
	Analog	-2.74	1.16		
	Digital	-3.57	1.07		
16 Hz	Unaided	-4.03	0.98	35.27**	2(114)
	Analog	-2.31	1.11		
	Digital	-3.10	1.11		
32 Hz	Unaided	-2.99	1.37	10.37**	2(96)
	Analog	-1.73	1.16		
	Digital	-2.44	1.27		
64 Hz	Unaided	-1.66	1.25	2.65	2(64)
	Analog	-0.88	1.05		
	Digital	-1.14	1.11		
128 Hz	Unaided	-0.78	1.03	0.60	2(23)
	Analog	-1.93	0.00		
	Digital	-1.54	1.78		

Note: * * - p<0.01

Table 3: Means and standard deviation (SD) of modulation thresholds in 3 experimental conditions across five different modulation frequencies.

Effect of experimental conditions on TMTF

Table III shows the means and standard deviation (SD) of modulation thresholds across 3 experimental conditions in the five different modulation frequencies. The table also shows the F value and the degrees of freedom representing the significance of difference across the conditions in terms of their modulation thresholds. Figure IV(a) and IV(b) shows comparison of TMTF across 3 experimental conditions separately for the 2 target groups. Results of ANOVA showed a significant main effect of condition on modulation thresholds in 8, 16 and 32 Hz modulation frequencies while the mean differences were not significantly different in 64 and 128 Hz. The frequencies in which thresholds were significantly different were further analyzed for pair-wise comparisons on Bonferroni post hoc test. Results of the post hoc test along with the mean thresholds (Table IV) can be summarized as follows.

1) Modulation thresholds are significantly better in the unaided condition compared to either of the aided conditions.

2) Modulation thresholds are significantly better for digital hearing aids compared to analog hearing aids.

MF (Hz)	Unaided vs Analog	Unaided vs Digital	Analog vs Digital
8	S	S	S
16	S	S	S
32	S	NS	S

S – p<0.05, NS – p>0.05

Table 4: Results of the post hoc test comparing across three experimental conditions in 8, 16 and 32 Hz modulation frequencies.

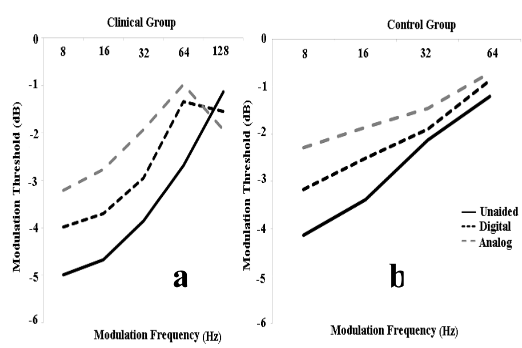

Figure 4: Comparison of TMTF across 3 experimental conditions in Normal hearing individuals (a) and individuals with sensorineural hearing loss (b).

Interaction between effect of groups and conditions

Results of two-way ANOVA (Table V) showed no significant interaction between the two independent variables (groups and the conditions) i.e, the effect of group and conditions were independent of each other. Because there was no interaction between effect of groups and conditions, comparisons within groups and within conditions were not necessary.

Modulation Frequency	F	df (Error)
8 Hz	0.036	2(114)
16 Hz	0.452	2(114)
32 Hz	2.508	2(96)
64 Hz	0.374	2(64)
128 Hz	-	0(23)

Table 5: F and degrees of freedom indicating the significance of interaction between effect groups and conditions.

Discussion

The results of the present study showed that modulation sensitivity reduced with the increase in modulation frequency. This is because, as modulation frequency increases, the amplitude fluctuations become increasingly smoothened as reported by Viemeister (1979). As a result, the subjects require greater amplitude change in order to resolve fluctuations. The result was same in normal hearing individuals as well as individuals with sensorineural hearing loss, and also is in agreement with the results of Drullman et al (1994).

The results of the present study showed that individuals with sensorineural hearing loss needed greater modulation depth to detect modulations compared to normal hearing individuals. This could be attributed to the cochlear pathology in individuals with sensorineural hearing loss. Although the modulated stimuli were presented at most comfortable levels to individuals with sensorineural hearing loss, compensating for their reduced audibility, modulation sensitivity remained poorer than that in normal hearing individuals. This is in agreement with most of the earlier studies (Hescot et al., 2000; Bacon & Viemeister, 1985; Ajith & Jayaram, 2004), but in contradiction with Moore and Glasberg (1988). The below normal TMTF in individuals with sensorineural hearing loss, even at most, comfortable levels is an evidence for the presence of deficits in temporal and spectral resolution in these individuals. The deficits in temporal resolution is attributed to the damage of physiologically vulnerable outer hair cells, the active process in the cochlea. Damage to the outer hair cells leads to reduced frequency selectivity, broadening of the frequency tuning curves which in turn results in decreased temporal resolution (Moore, 1991).

Earlier investigations have demonstrated that consonant identification and sentence intelligibility could be achieved if the modulation sensitivity is normal atleast upto 50 Hz (Shannon et al., 1995; Xu et al., 2005; Durllman, Festen & Plomp, 1994). In the present study individuals with cochlear pathology had reduced modulation sensitivity even at 8 and 16 Hz modulation frequencies. Hence, consonant identification and sentence intelligibility is expected to be degraded in these individuals. In the presence of background noise, speech is perceived based on its envelope (Tasell, 1987). In the present study, it was found that individuals with sensorineural hearing loss have problems in resolving the modulations in the envelope. Hence, it can be inferred from the present study that individuals with sensorineural hearing loss shall have problems in speech perception in noisy environments. Furthermore, temporal resolution is necessary for the perception of rhythm and segmentation of units in continuous speech (Miller, 1947). In the present study, individuals with sensorineural hearing loss had poorer modulation thresholds in lower as well as higher modulation frequencies compared to normal hearing individuals. Hence, it can be inferred that a person with sensorineural hearing loss will not be able to segment the speech units and perceive the regularity of speech (rhythm), the way normal hearing individuals do. Such a difficulty should increase with fast rate of speech.

The perception of rhythm in speech is based on the temporal changes in the speech envelope (Miller, 1947). Unlike segmentation of speech units, to perceive rhythm, normal modulation sensitivity at lower modulation frequencies is sufficient. However, in the present study, individuals with sensorineural hearing loss had poorer modulation sensitivity even at lower modulation frequencies like 8 and 16 Hz. Rhythm perception deficits reported in individuals with SNHL (Miller, 1947) are probably due to their poor temporal resolution at lower modulation frequencies, as evidenced in the present study.

Results of the present study also showed a significant effect of condition on modulation sensitivity. Irrespective of the modulation frequency and/or group, sensitivity was better in the unaided condition compared to that in the aided conditions. This difference shows the inability of hearing aids to reduplicate the envelope of the signal with 100% fidelity. With the hearing aids, both normal and hearing impaired individuals required an additional depth of about 1.5 dB to perceive the modulations. Hence, it can be concluded that though hearing aids are helping the hearing impaired in term of audibility, the present technology is not sufficient to enhance the temporal resolution in individual with cochlear pathology.

Furthermore, modulation sensitivity was poorer in analog hearing aids compared to digital hearing aids. This is because of the difference in the type of processing of signals. With digital processing, the signal is amplified with lesser distortions in terms of its envelope compared to an analog hearing aid. Furthermore such distortions increase with the modulation frequency of the envelope. In general, modulation sensitivity reduced by about 1.5 dB in analog hearing aids compared to digital hearing aids. Hence, from these results it is recommended that a digital hearing aid be prescribed to individuals with sensorineural hearing loss, to enhance temporal resolution along with improving the audibility.

There was no significant interaction between the effect of group and condition. That means the effect of group and the effect of condition was independent of each other.

Conclusions

From the results of the present study, the following conclusions can be drawn:

1. Temporal resolution is affected in individuals with mild to moderate sensorineural hearing loss even at lower modulation frequencies.
2. Hearing aids do not help in enhancing temporal resolution to a greater extent.
3. Among analog and digital hearing aids, digital hearing aids will aid better in resolving the envelope of speech.

References

Ajith, U., & Jayaram, M. (2004). Auditory processing in individuals with auditory neuropathy. *Ear and Hearing, 25* ,34-46.

Bacon, S. P., & Viemeister, N. F. (1985). Temporal modulation transfer functions in normal-hearing and hearing impaired subjects. *Audiology, 24,* 117 -134.

Dimitrijevic A., John M.S., & Picton T.W. (2004). Auditory steady state response and word recognition scores in normal hearing and hearing impaired adults. Ear *and Hearing, 25(1),* 68-84.

Drullman, R., Festen, J.M., & Plomp, R. (1994). Effect of temporal envelope smearing on speech reception. *Journal of Acoustical Society of America, 95(2),* 1053-1064.

Forrest, T. G & Green D. M (1987). Detection of partially filled gaps in noise and the temporal modulation transfer function. *Journal of Acoustical Society of America, 82 (6),* 1933-1943.

Glasberg, B. R., Moore, B. C. J., & Bacon, S. P. (1987). Gap detection and masking in in hearing impaired and normal-hearing subjects. *Journal of Acoustical Society of America, 81,* 1546-1556.

Hescot, F., Lorenzi, C., Debruille X., & Camus, J. F. (2000). Measurement of the temporal modulation transfer function for a single listener with cochlear hearing loss and left hemisphere damage. *British Journal of Audiology, 34,* 341-351.

Miller, G. A. (1947). The masking of speech. *Psychological Bulletin, 44,* 105-129.

Moore, B. C. J. (1991). Characterization and Simulation of Impaired Hearing: Implications for Hearing Aid Design. *Ear and Hearing, 12(6),* 154S-161S.

Moore, B. C. J., & Glasberg, B. R. (1988). Gap detection with sinusoids and noise in normals, impaired, and electrically simulated ears. *Journal of Acoustical Society of America, 83,* 1093-1101.

Rawool, V. W. (2006). The effect of hearing loss on temporal processing. *Hearing Review, 13,* 30-34.

Samelli, A. G., & Schochat, E. (2008). Study of REA on Gap Detection tests. *Otorrinolaryngology, 74* (2), 235-240.

Shanon, R. V., Zeng, F. G., Kamath, V., Wygonski, J., & Ekelid, M. (1995). Speech recognition with primarily temporal cues. *Science, 270,* 303-304.

Stuart, A. (2005). Development of auditory temporal resolution in school aged children revealed by word recognition in continuous and interrupted noise. *Ear and Hearing, 26(1),* 78-88.

Tasell, D. J. V. (1987). Speech waveform envelop cues for consonant recognition. *Journal of Acoustical Society of America, 82,* 1152-1160.

Vandana, S. (1998). *Speech identification test for Kannada speaking children.* Unpublished independent project, University of Mysore, Mysore, India.

Viemeister, N.F. (1979). Temporal modulation transfer functions based upon modulation thresholds. *Journal of Acoustical Society of America, 66(5),* 1364-1378

Xu, L., Thompson, C., & Pfingst, B. E. (2005). Relative contributions of spectral and temporal cues for phoneme recognition. *Journal of Acoustical Society of America, 117,* 3255-3267.