Developmental Changes in Comodulation Masking Release for Puretones: A Cross-Sectional Study

[1]Dhatri S. Devaraju & [2]Mamatha N. M.

Abstract

Comodulation Masking Release (CMR) is the phenomenon where there is enhancement in the signal detection when the fluctuations in the masker are correlated across different frequency bands. The development of CMR was studied in the present study across the age range 5 to 25 years at octave frequencies from 500 Hz to 4000 Hz. The participants were divided into 4 sub-groups according to their age. Two measures of CMR were measured based on the interaction of across channel and within channel cues underlying CMR. CMR1 was the difference between the signal detection in flanking band and comodulated masker condition. CMR2 was the difference between the signal detection in modulated on frequency band and comodulated masker condition. The results revealed a significant difference across age group in CMR1 at 500 Hz and in CMR2 at 1000 Hz. The significant difference was also noted between CMR1 and CMR2 in the age groups 10-15 years, 15- 20 years and 20-25 years. There was also significant difference noted in amount of CMR2 across frequencies in 10-15 years, 15-20 years and 20-25 years, whereas only in 20-25 years group CMR1 was significantly different across frequencies. From the results, it can be concluded that when only across channel cues are responsible for CMR, it develops by 20 years of age. But when both within channel cue and across channel cues are available, even 10 years and older perform equally.

Keywords: *Comodulation Masking Release (CMR), across channel cues, within channel cues, on frequency band masker, comodulated masker.*

Introduction

The peripheral auditory system contains an array of band pass filters, called the auditory filters, each tuned to a different centre frequency. When a subject tries to detect a sinusoidal signal in noise, it has traditionally been assumed that performance is based on the output of the single auditory filter which gives the highest signal-to-masker ratio. However, recent experiments demonstrate the ability to compare the outputs of different auditory filters to enhance signal detection. This enhancement takes place especially when the envelope of the masker fluctuates over time, and when the fluctuations are coherent or correlated across different frequency bands. This phenomenon is called Comodulation Masking Release (Hall, Haggard & Fernandes, 1984).

Comodulation Masking Release (CMR) can be determined in two ways. One way is by finding the difference in signal detection with random noise and random noise modulated at a low rate. Another way is by establishing the difference in signal detection using an on-frequency band centered at signal frequency and in flanking band masker, where flanking bands are modulated at the same rate as of on-frequency band. CMR occurs over a wide range of signal frequencies (500 Hz - 4000 Hz), and does not vary greatly with signal frequency (Haggard, Hall & Grose, 1990). CMR is largest when the modulation of the masker is at low rate, and when the masker covers a wide frequency range (Carlyon, Buus & Florentine, 1989). Eddins and Wright (1994) investigated that the CMR decreased from about 19 to 2 dB as modulation depth decreased, regardless of similar or different fluctuations used with respect to the carrier noise. CMR falls in the range of 1 to 6 dB when the flanking band is distant in frequency from the on-frequency band. The release from masking can be as large as 14 dB when flanking band is close in frequency to the on-frequency band. In this case within-channel cues probably influence the release from masking to be more. CMR measured with a flanking band presented in the opposite ear to the signal plus masker varies little with center frequency, but it is slightly larger for flanking bands close to the signal frequency than for flanking bands farther away (Hall, Grose & Haggard, 1990). CMR measured with an on-frequency band and a flanking band tends to increase as the width of the bands of noise is decreased (Schooneveldt & Moore, 1987). This is probably a consequence of the fact that the rate of envelope fluctuations decreases as the bandwidth decreases and slow fluctuations lead to large CMR. CMR also increases if more than one flanking band is used (Hall, Grose & Haggard, 1990). When multiple bands are used, CMR can be as large as 16 dB (Moore & Shailer, 1991).

[1]E-mail: dhatri2612@gmail.com; [2]Lecturer in Audiology, E-mail: mamms_20@rediffmail.com

It has been suggested that there can be both within-channel and across-channel cues responsible for the comodulation masking release (Grose, Buss, & Hall, 2009; Buss & Hall, 1998). There is a regular beating pattern between two flanking bands when they are close together. This beating pattern is disrupted by addition of a signal which serves as a within channel cue underlying CMR. Whereas when the masker bandwidth is greater, there is comparison in each channel happening. The spectral peak at the channel where the signal is present will act as a cue when there is across-channel comparison. These across-channel and within-channel cues may act differently at different frequencies when different masker bandwidths are used.

The development of CMR has been studied. A study by Veloso, Hall and Grose (1990) showed no significant difference in the abilities of 6 year old children and adults to detect a pure tone signal in a relatively wideband noise background. However, when the masker consisted of 3 bands of modulated noise, the masked thresholds of the children were consistently 2 to 5 dB higher than those of the adult listeners. Similar results were found by Hall, Grose and Dev (1997), who found 2 dB higher thresholds in adults when compared to 5 to 11 year old children. But the difference was not statistically significant. Zettler, Sevcik, Morris and Clarkson (2008) also evaluated the development of CMR. Although total CMR did not change from 7 to 10 years of age, total CMR for children (4.02 dB) was significantly less than that for adults (10.85 dB), suggesting that across-channel processing develops after 10 years of age. In addition, thresholds for children were significantly higher than those for adults in both the on frequency band condition (by 6.47 dB) and the modulated masker condition (by 13.91 dB), supporting the likelihood that processing efficiency also develops beyond 10 years of age. These results suggest that both processing efficiency and across-channel cues utilized in CMR are slowly developing phenomena.

Need for the study

CMR measures a listener’s ability to use temporal and spectral information in noise (Zettler, Sevcik, Morris & Clarkson, 2008). In addition, physiological studies suggest that CMR could be a consequence of wideband inhibition at the level of the cochlear nucleus (Pressnitzer, Meddis, Delahaye & Winter, 2001; Ernst & Verhey, 2006). Studies further suggest that central effects may play a significant role in CMR (Buss & Hall, 2008). The children with central auditory processing disorders will have impaired processing of temporal and spectral information. Thus, CMR can be used as a behavioral tool to assess a function of central auditory processes in these children.

But there is dearth in literature about the age at which this advantage of CMR develops. Most of the previous studies focus on CMR in children less than 10 years of age and results indicate that CMR may develop after 10 years of age (Veloso, Hall & Grose 1990; Hall, Grose & Dev, 1997; Zettler et al., 2008).

Also, these studies have used a single frequency of 1000 Hz to compare the amount of CMR between children and adults. Thus, there is a need for further research using a CMR paradigm at different frequencies with older children which would illuminate the developmental picture of CMR. Studies focusing on within-channel and across-channel cues underlying CMR are done only in adults (Grose, Buss & Hall, 2009; Buss & Hall, 1998). Hence, there is a need to study how within-channel and across-channel cues underlying CMR develops in children.

The aim of the present study was to analyze the amount of comodulation masking release for pure tones 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz in different age groups i.e., 5-10 years, 10-15 years, 15-20 years, and 20-25 years and to compare the amount of CMR across frequencies. Present study also aimed at comparing the amount of comodulation masking release across different age groups to see the developmental trend. The study also aimed at comparing across-channel and within-channel cues responsible for CMR at different frequencies in each age group.

Method

Participants

A total of 64 participants (35 males & 29 females) in the age range of 5 to 25 years were taken for the study. The participants were divided into 4 subgroups based on their age. Group 1 consisted of 16 participants (10 males & 6 females) in the age range of 5 to 10 years with a mean age of 8.44 years. Group 2 consisted of 16 participants (11 males & 5 females) in the age range of 10 to 15 years with a mean age of 13.13 years. Group 3 consisted of 16 participants (8 males & 8 females) in the age range of 15 to 20 years with a mean age of 18.06 years. Group 4 consisted of 16 participants (6 males & 10 females) in the age range of 20 to 25 years with a mean age of 23 years. All the participants had air conduction thresholds and bone conduction thresholds within 15 dBHL at octave frequencies from 250 Hz to 8 kHz and 250 Hz to 4 kHz respectively (ANSI S3.21, 2004). There was no history of otological, neurological or any middle ear disorders.

The participants who had good speech perception in noise with SPIN scores of more than 60% were considered for the study.

Test Environment

All the experiments were done in a sound treated double room situation. The ambient noise levels were within permissible limits as per ANSI S3.1; 1999 (R2003).

Equipment

A calibrated two-channel Madsen Orbiter-922 clinical audiometer (Version 2) with TDH-39 headphones and Radio ear B-71 bone vibrator were used to establish air conduction and bone conduction pure tone thresholds respectively. A calibrated Grason Stadler Inc.-Tympstar immittance meter (Version 2) was used to record tympanogram and acoustic reflexes. A Personal Computer with Matlab version 7.8 was used to generate the stimulus. An Apex 3 program developed at ExpORL (Francart, van Wieringen, & Wouters, 2008) was used to deliver the stimulus in three-interval, three alternate forced choice (3IAFC), three-down-one-up procedure and also to record the responses. Tucker - Davis Technologies (TDT) system with RP2.1 processor was used to reproduce the test stimulus at a sampling rate of 50 K, which was routed through a PA5 programmable attenuator. This stimulus was presented through a Sennheiser HDA-200 headphone using a HB7 headphone buffer.

Stimulus generation: All the stimuli were generated using Matlab version 7.8. All the stimuli were generated according to the description given by Hall, Haggard and Fernandes (1984). The following different types of maskers were generated.

Narrow band masker without modulation: A narrow band noise of 100 Hz bandwidth centered on signal frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were generated. This narrow band masker is called on-frequency band (OFB). Each of it was 600 ms in duration with a rise and fall time of 50 ms. This led to 4 different masker conditions as given in Table 1.

Flanking band masker: The narrow band maskers centered at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were added with 6 flanking bands. Each flanking band was a narrow band noise of 100 Hz bandwidth. The flanking bands were added such that it results in 3 bands on either side of narrow band masker. For example, at 1000 Hz, the narrow band noise had a bandwidth from 950 Hz - 1050 Hz. This narrow band noise was added with 3 flanking bands below it i.e., noise frequency bands of 850 Hz - 950 Hz, 750 Hz - 850 Hz and 650 Hz - 750 Hz. In the same way 3 bands were added above the narrow band noise i.e., 1050 Hz - 1150 Hz, 1150 Hz - 1250 Hz and 1250 Hz - 1350 Hz. When these flanking bands were added to narrow band masker (on frequency band) of 1000 Hz, it resulted in flanking band masker at 1000 Hz. Each of it was 600 ms in duration with a rise and fall time of 50 ms. This resulted in 4 masker conditions given in Table 1.

Modulated on frequency band masker: The on-frequency bands i.e., narrow band maskers centered at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz was 100% amplitude modulated by multiplying a 10 Hz pure tone. This gave away the next 4 masker conditions given in Table 1.

Comodulated masker: Each of the 6 flanking bands of 100 Hz bandwidth were 100% amplitude modulated separately at 10 Hz using pure tone. These flanking bands were added to the modulated on frequency band masker of center frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. The flanking bands were added such that it resulted in 3 bands on either side of modulated on frequency band masker. As all bands of noise are modulated at 10 Hz, the resulting noise can be called as comodulated masker. It gave rise to 4 more masker conditions as shown in Table 1.

Pure-tone signals of frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were generated at 44100 Hz sampling rate with a 16-bit resolution. The duration of each pure-tone signal was of 400 ms with 50 ms rise time and fall time. The pure tone of frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were added with the 4 types of maskers i.e., on-frequency band masker, flanking band masker, modulated on-frequency band masker, and comodulated masker of corresponding centre frequencies. The puretone was mixed in such a way that it is placed in centre temporally with 600 ms duration of noise. The masker levels for all 16 masker conditions were kept constant at 50 dBSPL. Pure tone level was varied from 0 dB to 60 dBSPL to estimate the threshold. Keeping the masker level constant, the test signals were obtained at different signal to noise ratios by varying the pure tone level. Using stimuli with different signal to noise ratio 3IAFC procedure was designed through Apex 3 platform.

A total of 16conditions were formed as mentioned earlier. A set of 3 stimuli were given in each trial. Two of them were only masker and one with both masker and pure tone. The duration of one stimulus was 600 ms. Thus for 3 stimuli, the total duration was 1800 ms. The inter-stimulus interval was 500 ms between any two stimuli in a trial.

Table 1: Different masker conditions at different frequencies

Conditions	500 Hz	1000 Hz	2000 Hz	4000 Hz
On frequency band with no modulation	500 Hz OFB-no mod	1000 Hz OFB-no mod	2000 Hz OFB-no mod	4000 Hz OFB-no mod
Flanking band masker	500 Hz-flank	1000 Hz-flank	2000 Hz-flank	4000 Hz-flank
Modulated on - frequency band	500 Hz OFB-mod	1000 Hz OFB-mod	2000 Hz OFB-mod	4000 Hz OFB-mod
Comodulated masker	500 Hz-comod	1000 Hz-comod	2000 Hz-comod	4000 Hz-comod

Test Procedure

Otoscopic examination of all subjects was done to rule out any outer ear and tympanic membrane pathologies. Air conduction pure tone thresholds at octave frequencies from 250 Hz to 8000 Hz and bone conduction thresholds at octave frequencies from 250 Hz to 4000 Hz were established for the participants using modified Hughson and Westlake (Carhart & Jerger, 1959) procedure to check for the normal hearing sensitivity. Tympanogram was obtained using 226 Hz probe tone frequency. Both ipsilateral and contralateral acoustic reflex threshold at frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were established to rule out middle ear pathology and to find the hearing sensitivity. Speech in Noise test was carried out to rule out any difficulty in speech perception in the presence of noise. The testing was done at 40 dB SL and 0 dB SNR. Speech noise was used as masker. The spondee wordlist developed by Yathiraj and Vijayalakshmi (2005) was used as speech stimuli. The participants who had SPIN scores of >60% at 0 dB SNR were considered for the further procedure.

Procedure to obtain Comodulation Masking Release (CMR): The ipsilateral pure tone masked thresholds was obtained in 16 masker conditions i.e., on-frequency band masker, flanking band masker, modulated on-frequency band masker, and comodulated masker at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz using three-interval, three alternate forced choice (3IAFC), three-down-one-up procedure, estimating 79.4 % signal detection (Levitt, 1971). One set of stimulus was associated with 3 no. of blocks represented by 1, 2 and 3. The 3 blocks of noise was presented out of which one had the tone. The subject was instructed to click on the no. of block in which he/she heard the tone or on the no. of block which he/she heard different. The presentation of tone in one of the three blocks was randomized. Appropriate reinforcement and feedback was given in terms of pictures after each trial**.** To establish pure tone thresholds, the initial step size of 8 dB was reduced to 2 dB after one reversal and after second reversal it was reduced to 1 dB. A run was terminated after eight reversals and the average of the last five reversals was taken as threshold. This was done using Apex 3 software. At the end of all the trials, 16 set of values were obtained when 4 masker conditions at 4 frequencies were considered. These values were used to calculate CMR in two ways i.e., CMR 1 and CMR 2.

CMR 1: Pure tone threshold difference between flanking band masker condition and comodulated masker condition at corresponding frequency gives CMR 1, which yielded 4 following measures

CMR 1 - 500 Hz
CMR 1 - 1000 Hz
CMR 1 - 2000 Hz
CMR 1 - 4000 Hz

CMR 2: Pure tone threshold difference between modulated on frequency band masker condition and comodulated masker condition of corresponding frequency gives CMR 2, which again yielded 4 following measures

CMR 2 - 500 Hz
CMR 2 - 1000 Hz
CMR 2 - 2000 Hz
CMR 2 - 4000 Hz

Analysis

The mean and standard deviation of pure tone thresholds were calculated for all the 16 conditions across different age groups. The CMR 1 and CMR 2 values at different frequencies across different age groups were considered for statistical analysis. Appropriate statistical analysis using Statistical Package for the Social Sciences (SPSS) version 17.1 software was done to compare CMR 1 and CMR 2 across different age groups, and also across different frequencies.

Results and Discussion

Comparison of CMR values at different frequencies across different age groups

The group means and standard deviation was obtained for two measures of CMR i.e., CMR1 and CMR2 independently at frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz across different age groups. The results are summarized in the Table 2. From the Table 2, it can be inferred that for Group 1, the mean changes in CMR 1 across different frequencies is around 1 dB. Whereas for other three groups, there is larger difference in CMR 1 across frequencies. Greater CMR 1 can be noticed for 500 Hz and 4000 Hz in the other three groups. CMR1 at 1000 Hz and 2000 Hz is lesser when compared to 500 Hz and 4000 Hz. It can also be noticed that the mean scores for CMR 1 increases from Group1 to Group 4 for 500 Hz and 4000 Hz, whereas it is not so for 1000 Hz and 2000 Hz. When CMR 2 is considered, with the increase in frequency, CMR 2 decreases. It can also be seen that there is increase in CMR 2 from Group 1 to Group 4 when 500 Hz is considered. Whereas for 1000 Hz, 2000 Hz and 4000 Hz, there is no particular trend seen.

Thus, mixed analysis of variance (mixed ANOVA) was done to see the significant interaction across age groups and frequencies for CMR measures. The results revealed a significant interaction across age groups [$F(3, 60)= 9.59$, $p<0.01$], across frequencies [$F(3, 180)=22.44$, $p<0.01$] and also across frequencies and age groups [$F(9, 180)=3.13$, $p<0.01$]. There was no significant difference noted for CMR across frequencies across different age groups [$F(9, 120)=0.83$, $p>0.01$].

Comparison of two CMR values across age groups

To compare CMR1 and CMR2 at different frequencies independently across age groups multi-variate analysis of variance (MANOVA) was used as mixed ANOVA showed a significant interaction of CMR measures across age groups. The results showed that there was significant difference across age groups for CMR1 at 500 Hz [$F(3, 60)=8.25$, $p<0.05$] and CMR2 at 1000 Hz [$F(3, 60)=5.42$, $p<0.05$]. There was no significant difference between age groups for CMR1 at 1000 Hz, 2000 Hz and 4000 Hz [$F(3, 60)=0.07$, 1.62 & 2.04 respectively at $p>0.05$] and also for CMR2 at 500 Hz, 2000 Hz and 4000 Hz [$F(3, 60)=1.24$, 0.69 & 1.66 respectively at $p>0.05$]. To arrive at the groups which are significantly different in CMR1 at 500 Hz, Duncan's post-hoc analysis was carried out. Results showed that Group 1 was significantly different from Group 2, Group 3 and Group 4 ($\alpha<0.05$). Group 2 was significantly different from Group 4 ($\alpha<0.05$). There was no significant difference between Group 2 and Group 3($\alpha>0.05$). No significant difference was found between Group 3 and Group 4 ($\alpha>0.05$).

These results are in congruence with the results obtained by Zettler et al., (2008). They got a CMR of 4.02 dB in children with a mean age of 8.95 years and 10.85 dB was found in adults with a mean age of 23.3 years. They determined CMR using modulated on frequency band and eight comodulated flanking bands. The CMR1 values got in the present study are little higher than those obtained by Zettler et al., (2008). This might be because of the increased amount of CMR seen when the on signal masker is of wider bandwidth, especially at lower frequencies in adults (Schooneveldt & Moore, 1989a; Haggard, Hall & Grose, 1990), which is 700 Hz in the present study. This stimulus paradigm i.e., 500 Hz signal frequency and masker bandwidth of 700 Hz is not used in children in any of the previous studies reported.

In the present study, the CMR1 at 500 Hz was 5.02 dB for children aged 5-10 years, increasing rapidly to 11.47 dB in children with the age range 10-15 years. It further tends to increase gradually after 15 years of age with 15.29 dB and 18.54 dB in the age range of 15-20 years and 20-25 years respectively. But there is no significant difference seen in CMR1 across different age groups at 1000 Hz and 2000 Hz. This might be because of the interaction of both within-channel and across-channel processing leading to lesser effect. Even though the increase in CMR1 across age groups can be evidenced at 4000 Hz, it was not statistically significant. This might be because of the high degree of variability within a group, or because of the only within-channel cue available at 4000 Hz for determining CMR in adults leading to lesser CMR compared to 500 Hz. Increase in CMR1 at 500 Hz with increase in age suggests that the across-frequency processing matures with age in children. There is increased amount of maturation taking place between 5-10 years and 10-15 years, whereas there is gradual amount of development taking place after 15 years of age till 20 years. Whether there is further development after 20 years or not could be determined if another age group extending from 25-30 years would have been considered. As of now, it can be said that across channel processing matures by 20 years.

As MANOVA showed significant difference for CMR2 at 1000 Hz, Duncan's post-hoc test was applied to arrive at groups that were significantly different. The results revealed a significant difference between Group 1 with Group 3 and Group 4 ($\alpha<0.05$). Group 2 was significantly different from Group 4 ($\alpha<0.05$). There

Table 2: Mean and standard deviation of CMR1 and CMR2 at different frequencies across different age groups

	500 Hz		1000 Hz		2000 Hz		4000 Hz	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
CMR1*								
Group 1 (5-10 years)	5.02	6.69	7.88	4.04	6.53	7.97	7.46	9.30
Group 2 (10-15 years)	11.47	7.20	8.53	5.78	7.03	6.77	11.91	4.87
Group 3 (15-20 years)	15.29	7.93	8.33	5.97	11.23	6.75	12.18	9.44
Group 4 (20-25 years)	18.54	10.12	8.76	6.10	9.43	5.79	15.19	10.88
CMR2*								
Group 1 (5-10 years)	6.98	10.13	5.26	6.68	-1.41	6.80	1.74	10.52
Group 2 (10-15 years)	7.96	9.50	1.18	6.99	-4.43	7.89	-0.49	5.87
Group 3 (15-20 years)	10.81	10.13	-3.83	11.48	-3.92	7.52	-4.23	8.53
Group 4 (20-25 years)	13.16	10.46	-7.24	11.49	-5.53	10.85	1.27	8.10

*Note: *CMR 1 = threshold (flanking band masker) – threshold (comodulated masker)*
**CMR 2 = threshold (modulated OFB masker) – threshold (comodulated masker)*

was no significant difference between Group 1 and Group 2, Group 2 and Group 3 and, Group 3 and Group 4 (α>0.05).

When CMR 2 at 1000 Hz is considered, there is reversal of trend seen as that of CMR1. Here the CMR2 values decreased as there is increase in age. This is contradicting to the previous studies done to measure CMR comparing children and adults, which says either there is increase in CMR (Zettler et al., 2008; Hall, Grose & Dev, 1997), or no change in CMR (Veloso, Hall & Grose, 1990). Even though Hall, Grose and Dev (1997) obtained a difference of 2 dB between children and adults, it was not statistically significant. But Zettler et al., (2008) obtained a significant difference between children and adults. The results in the present study concerning difference in CMR2 may be because of certain developmental factors. Possible explanations for developmental effects involve anatomical and mechanical factors (eg. developing auricle, external auditory canal, and middle ear structures), sensori-neural factors, and attentional factors (Olsho, 1986; Rubel & Ryals, 1983; Schneider, Trehub, Morrongiello & Thorpe, 1986). The negative values of CMR2 at higher frequencies in adults might be because of the lesser bandwidth of the masker used in the present study. However, children with age range of 5-10 years got positive CMR2. This might be because of the interruption of the beating pattern created between two flanking bands by the addition of a pure tone that acts as a within channel cue, enhancing the signal detection (Buss & Richards, 1996). There was no difference observed in amount of CMR1 and CMR2 in 5-10 years old children. This probably suggests that frequency selectivity for the across frequency comparisons continues to mature gradually along with the increasing age. And also, the within channel cues might be playing a role in children which cannot be considered as true CMR (Schooneveldt & Moore, 1989b). When CMR2 is considered, there is a trend seen at 500 Hz and 2000 Hz across age groups. CMR2 increases at 500 Hz and decreases at 2000 Hz, with increase in age. But it was not statistically significant might be because of the increased variability across subjects within a group.

Comparison of two CMR values across frequencies in each age group

To see the significant difference across the frequencies within each age group for CMR1, repeated measure ANOVA was done. The results showed a significant difference in CMR1 across frequencies for Group 4 [$F(3, 45)=7.40$, $p<0.05$]. There was no significant difference across frequencies for Group 1, Group 2 and Group 3 [$F(3, 45)=0.75$, 2.11 & 2.43 respectively at $p>0.05$]. As repeated measure ANOVA showed significant difference across frequencies for Group 4, Bonferroni's multiple pair wise comparison test was carried out. The results showed a significant difference between 500 Hz and 1000 Hz and, 500 Hz and 2000 Hz at a 0.05 level of significance. There was no significant difference between 500 Hz and 4000 Hz, 1000 Hz and 2000 Hz, 1000 Hz and 4000 Hz and, 2000 Hz and 4000 Hz at a 0.05 level of significance.

CMR1 is the difference in thresholds obtained from flanking band masker condition and comodulated masker condition. The bandwidth of the masker was approximately 700 Hz in both the masker condition. We know that critical bandwidth increases as frequency increases (Moore & Glasberg, 1983; Dubno & Dirks, 1989; Shailer, Moore, Glasberg, Watson & Harris 1990; Moore, Peters & Glasberg, 1990). Thus, at 500 Hz, since the critical bandwidth is 120 Hz, there are enough bands available on either side of the centre on frequency band to compare the signal across different frequency channels. This helps in detecting a spectral peak at the centre frequency when there is masker minimum. Thus, larger CMR can be seen at 500 Hz in Group 4 as a result of across-channel processing. This has been evidenced in a study by Haggard, Hall and Grose (1990). The CMR was measured as function of bandwidth across frequencies from 500 Hz to 4000 Hz. The CMR was determined as the difference between the pure tone threshold obtained in modulated and unmodulated masker of corresponding bandwidth. There was no measurable CMR at 2000 Hz and 4000 Hz when the bandwidth was lesser than or equal to 200 Hz and 400 Hz respectively.

When 4000 Hz is considered, the critical bandwidth of the filter is around 500 Hz. Then there will be lesser bands available on either side of on frequency band to compare across channels because the bandwidth of masker used in the present study was 700 Hz. Thus, it can be speculated that there might be within channel cue that is responsible for greater CMR 1 at 4000 Hz. That is there might be disruption of beating pattern in the 4000 Hz channel by the introduction of pure tone, enhancing the detection. Hence, since the across channel processing leads to greater CMR at 500 Hz, there might be significant difference seen between 500 Hz and 1000 Hz & 2000 Hz. Whereas at 4000 Hz, since only within channel processing is taking place, the amount of CMR is little lesser than what was seen at 500 Hz. But it is not significantly lesser. At 1000 Hz and 2000 Hz, there is neither across-channel cue nor within channel cue dominating in significant masking release. There might be interaction of both across-channel and within channel cue leading to the lesser CMR. Thus, to establish CMR based on across-channel processing, the bandwidth of the masker should be more than critical bandwidth of corresponding frequency channel. Overall, the results suggests the notion that the across channel processing and frequency selectivity develops till the age of 20 years (Zettler et al., 2008).

Similarly, for CMR 2, to see the significant difference across the frequencies within each age group, repeated measure ANOVA was carried out. There was significant difference in CMR 2 across different frequencies in Group 2, Group 3 and Group 4 [$F(3, 45)=5.96$, 11.08 & 17.04 respectively at $p<0.05$] except Group 1 [$F(3, 45)=3.08$, $p>0.05$]. As repeated measure ANOVA showed significant difference across frequencies for Group 2, Group 3 and Group 4, Bonferroni's multiple pair wise comparison test was done. In Group 2, significant difference was noted only for 500 Hz and 2000 Hz. When Group 3 and Group 4 were considered, 500 Hz was significantly different from 1000 Hz, 2000 Hz and 4000 Hz at a level of significance of 0.05. But there was no significant difference found between any of the other pairs. The result showed no difference across frequencies in Group 1. This suggests that within channel and across channel cues that are essential for CMR2, develops at a certain age after 10 years (Zettler et al., 2008). When group 2 is considered, the difference is seen only between 500 Hz and 2000 Hz, which suggests a scope of development. Whereas for Group 3 and Group 4 similar trend in the differences across frequencies can be seen suggesting that the development of within channel v/s across channel processing takes place by the age of 15 years. CMR2 decreases with increase in frequency. This is in accordance with the previous studies which showed reduced CMR at higher frequencies (Schooneveldt & Moore, 1987; Haggard, Hall & Grose, 1990; Fantini, Moore, & Schooneveldt, 1993). In a study by Haggard, Hall and Grose (1990), the largest value of masking release obtained decreased from +3.7 dB at 500 Hz to -4.5 dB at 4 kHz. Even in the present study, negative CMR of similar magnitude can be seen at 2000 Hz and 4000 Hz. This might be because of the consequence of the bandwidth of the modulated on frequency band masker which was 100 Hz. Hence, according to power spectrum model, the amount of noise passing through the filter at higher frequencies is lesser. This is because the critical bandwidth is 300 Hz at 2000 Hz and around 500 Hz at 4000 Hz which is greater when compared to on frequency noise bandwidth. This improves the signal to noise ratio at particular auditory filter making the threshold for signal detection better. Whereas for comodulated masker condition, the bandwidth is 700 Hz, which is a little higher than the critical bandwidth. This results in more amount of noise passing through the auditory filter compared to only 100 Hz bandwidth of modulated on frequency band masker. Thus, the thresholds obtained in comodulated masker condition will be increased when compared to modulated on frequency band masker condition. Also, there is no across channel cue available as there are not enough bands surrounding centre band at high frequencies. This leads to negative CMR.

Comparison of CMR1 and CMR2 at each frequency in each group

Paired t-test was done to compare CMR1 and CMR2 at each frequency in each group. In group 1, there was significant difference between CMR1 and CMR2 at 1000 Hz and 2000 Hz ($t=2.18$, $p=0.045$ and $t=3.86$, $p=0.002$ respectively, at p value 0.05). There was no significant difference when 500 Hz and 4000 Hz were considered in Group 1. There was significant difference between CMR1 and CMR2 at all the 4 frequencies for Group 2 [($t=2.547$, $p=0.022$), ($t=3.692$, $p=0.002$), ($t=7.491$, $p=0.000$) & ($t=7.990$, $p=0.000$) at 500 Hz, 1000 Hz, 2000 Hz & 4000 Hz respectively, at p value 0.05], Group 3 [($t=2.928$, $p=0.010$), ($t=4.871$, $p=0.000$), ($t=6.246$, $p=0.000$), & ($t=7.144$, $p=0.000$) at 500 Hz, 1000 Hz, 2000 Hz & 4000 Hz respectively, at p value 0.05], and Group 4 [($t=2.829$, $p=0.013$), ($t=6.045$, $p=0.000$), ($t=5.834$, $p=0.000$) & ($t=7.502$, $p=0.000$) at 500 Hz, 1000 Hz, 2000 Hz & 4000 Hz respectively, at p value 0.05].

The studies carried out on children suggest that the masked thresholds are generally higher for children when compared to adults (Allen, Wightman, Kistler, & Dolan, 1989; Irwin, Stillman & Schade, 1986; Nozza & Wilson, 1984). This effect is more for a narrow band noise when compared to a wide band noise (Veloso, Hall & Grose, 1990). These age-related differences are greater for low-frequency stimuli than for high-frequency stimuli (Irwin, Ball, Kay, Stillman & Bosser, 1985; Wightman, Allen, Dolan, Kistler & Jamieson, 1989). But the results obtained in the present study shows a difference in CMR1 and CMR2 at 1000 Hz and 2000 Hz, but not at 500 Hz and 4000 Hz in children with the age range of 5-10 years. This might be because of the availability of predominant across channel cue and within channel cue at 500 Hz and 4000 Hz respectively (Haggard, Hall & Grose, 1990; Schooneveldt & Moore, 1987). But when they have to compare using both within channel and across channel cues at 1000 Hz and 2000 Hz, the difference in CMR1 and CMR2 can be seen because of different stimulus characteristics that are used. The difference between the CMR1 and CMR2 can be seen after the age of 10 years at all frequencies. This suggests that the within channel and across channel comparison for CMR takes place after the age of 10 years (Zettler et al., 2008). Thus, it can be concluded that when using only across channel comparisons for CMR, there is developmental changes seen and it matures at 20 years of age. But when within channel cue is available with across channel comparisons, it probably matures by the age of 10 years.

Conclusions

The enhancement in signal detection when the envelope of the masker fluctuates over time, and when the fluctuations are coherent or correlated across different frequency bands has been referred to as Comodulation Masking Release (Hall, Haggard & Fernandes, 1984). It has been suggested that there can be both within channel and across channel cues responsible for the comodulation masking release (Grose, Buss & Hall, 2009; Buss & Hall, 1998). These across channel and within channel cues may act differently at different frequencies when different masker bandwidth is used. But studies concerning the development of CMR have employed one particular masker bandwidth studying CMR at single frequency. They have shown that the across channel processing required for CMR and also the processing efficiency develops after 10 years of age (Veloso, Hall & Grose, 1990; Hall, Grose & Dev, 1997; Zettler et al., 2008). Thus, present study was carried-out to study development of CMR using different frequencies.

From the results, it can be concluded that CMR is a slowly developing phenomenon. When CMR1 is examined at 500 Hz, the development is rapid between the age of 5 - 10 years and 10 - 15 years, after which it matures gradually. Correlating with the previous studies, it can be speculated that the across channel processing responsible for the CMR develops by the age of 20 years. Since the present study did not consider after the age of 25 years, it cannot be concluded that CMR matures by the age of 20 years. When CMR2 is considered, ideally there should be negative value of CMR that should be obtained at higher frequencies because of the masker bandwidth (700 Hz) that is taken in the present study. But there was no significant difference that was noticed in amount of CMR2 across frequencies in children less than 10 years of age. Also, there was no significant difference noted across frequencies until 20 years of age when CMR1 was considered. This probably suggests that processing efficiency at different frequencies and the comparison of both across channel and within channel cues to determine CMR develops till the age of 20 years.

CMR measures a listener's ability to use temporal and spectral information in noise to identify a signal. Thus, it can be used in assessing children with auditory processing disabilities (APD) who have difficulty processing temporal and spectral components of sounds. The present study adds on to the literature on when CMR develops and how does across and within channel cues in CMR contribute in this development. The data of the present study can be used to compare the amount of CMR in individuals with impaired temporal and spectral processing across different age groups.

References

Allen, P., Wightman, F., Kistler, D., & Dolan, T. (1989). Frequency resolution in children. *Journal of Speech & Hearing Research*, *32*, 317-322.

American National Standards Institute. (2003). *Maximum permissible ambient noise levels for audiometric test rooms* (ANSI S3.1-1999; Rev. ed.). Author: New York.

American National Standards Institute. (2004). *Methods for manual pure-tone threshold audiometry* (ANSI S3.21-2004). Author: New York.

Buss, E., & Hall, J. W. (1998). The role of auditory filters in comodulation masking release (CMR). *Journal of the Acoustical Society of America, 103,* 3561-3566.

Buss, E., & Hall, J. W. (2008). Factors contributing to comodulation masking release with dichotic maskers. *Journal of the Acoustical Society of America, 124,* 1905-1908.

Buss, E., & Richards, V. M. (1996). CMR and factors influencing grouping: Masker bands overlapping in frequency. *Journal of the Acoustical Society of America, 100,* 1897-1900.

Carhart, R., & Jerger, J. (1959). Preferred method of clinical determination of puretone threshold. *Journal of Speech & Hearing Disorders, 24*, 330-345.

Carlyon, R. P., Buus, S., & Florentine, M. (1989). Comodulation masking release for three types of modulator as a function of modulation rate. *Hearing Research, 42*, 37-46.

Dubno, J. R., & Dirks, D. D. (1989). Filter characteristics and consonant recognition for hearing-impaired listeners. *Journal of the Acoustical Society of America , 85*, 1666-1675.

Eddins, D., & Wright, B. A. (1994). Comodulation masking release for single and multiple rates of envelope fluctuation. *Journal of the Acoustical Society of America*, *96,* 3432-3442.

Ernst, S. M., & Verhey, J. L. (2006). Role of suppression and retro-cochlear processes in comodulation masking release. *Journal of the Acoustical Society of America, 120*, 3843-3852.

Fantini, D. A., Moore, B. C. J., & Schooneveldt, G. P. (1993). Comodulation masking release as a function of type of signal, gated or continuous masking, monaural or dichotic presentation of flanking bands, and center frequency. *Journal of the Acoustical Society of America*, *93*, 2106-2115.

Francart, T., VanWieringen, A., & Wouters, J. (2008). "APEX-3: A multi-purpose test platform for auditory psychophysical experiments". *Journal of Neuroscience Methods*, *172*(2), 283--293.

Grose, J. H., Buss, E., & Hall, J. W. (2009) Within- and across-channel factors in the multiband comodulation masking release paradigm. *Journal of the Acoustical Society of America, 125*, 282-293.

Haggard, M. P., Hall, J. W., & Grose, J. H. (1990). Comodulation masking release as a function of bandwidth and test frequency. *Journal of the Acoustical Society of America, 88*, 113-118.

Hall, J. W., Grose, J. H., & Dev, M. B. (1997). Auditory development in complex tasks of comodulation masking release. *Journal of Speech Language & Hearing Research, 40*, 946-954.

Hall, J. W., Grose, J. H., and Haggard, M. P. (1990). Effects of flanking band proximity, number, and modulation pattern on comodulation masking release. *Journal of the Acoustical Society of America*, *87,* 269–283.

Hall, J. W., Haggard, M. P., & Fernandes, M. A. (1984). Detection in noise by spectro-temporal pattern analysis. *Journal of the Acoustical Society of America*, *76,* 50-56.

Irwin, R. J., Ball, A. K., Kay, N., Stillman, J. A., & Bosser, J. (1985). The development of auditory temporal acuity in children. *Child Development, 56*, 614-620.

Irwin, R. J., Stillman, J. A., & Schade, A. (1986). The width of the auditory filter in children. *Journal of Experimental Child Psychology, 41*, 429-442.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, *49*, 467-477.

Moore, B. C. J., & Glasberg, B. R. (1983). Suggested formulae for calculating auditory-filter bandwidths and excitation patterns. *Journal of the Acoustical Society of America , 74*, 750-753.

Moore, B. C. J., & Shailer, M. J. (1991). Comodulation masking release as a function of level. *Journal of the Acoustical Society of America*, *90,* 829-835.

Moore, B. C. J., Peters, R. W., & Glasberg, B. R. (1990). Auditory filter shapes at low center frequencies. *Journal of the Acoustical Society of America, 88,* 132-140.

Nozza, R. J., & Wilson, W. R. (1984). Masked and unmasked pure-tone thresholds of infants and adults: Development of auditory frequency selectivity and sensitivity. *Journal of Speech & Hearing Research*, *27*, 613-622.

Olsho, L. W. (1986). Early development of human frequency resolution. In R. J. Ruben, T. R. VanDeWater, & E. W. Rubel (Eds). *The biology of change in otolaryngology* (pp. 71-90). Elsevier: Amsterdam.

Pressnitzer, D., Meddis, R., Delahaye, R., & Winter, I. M. (2001). Physiological correlates of comodulation masking release in the mammalian ventral cochlear nucleus. *Journal of Neuroscience, 21,* 6377-6386.

Rubel, E. W., & Ryals, B. M. (1983). Development of the place principle: Acoustic trauma. *Science, 219*, 512-514.

Schneider, B. A., Trehub, S. E., Morrongiello, B. A., & Thorpe, L. A. (1986). Auditory sensitivity in preschool children. *Journal of the Acoustical Society of America*, *79*, 447-452.

Schooneveldt, G. P., & Moore, B. C. J. (1987). Comodulation masking release (CMR): Effects of signal frequency, flanking-band frequency, masker bandwidth, flanking-band level, and monotic versus dichotic presentation of the flanking band. *Journal of the Acoustical Society of America, 82,* 1944-1956.

Schooneveldt, G. P., & Moore, B. C. J. (1989a). Comodulation masking release (CMR) as a function of masker bandwidth, modulator bandwidth and signal duration. *Journal of the Acoustical Society of America, 85,* 273-281.

Schooneveldt, G. P., & Moore, B. C. J. (1989b). Comodulation masking release (CMR) for various monaural and binaural combinations of the signal, on-frequency, and flanking bands. *Journal of the Acoustical Society of America*, *85,* 262-272.

Shailer, M. J., Moore, B. C.J., Glasberg, B. R., Watson, N., & Harris, S. (1990). Auditory filter shapes at 8 and 10 kHz. *Journal of the Acoustical Society of America*, *88*, 141-148.

Veloso, K., Hall, J. W., & Grose, J. H. (1990). Frequency selectivity and comodulation masking release in adults and in 6 year-old-children. *Journal of Speech and Hearing Research, 33,* 96-102.

Wightman, F., Allen, P., Dolan, T., Kistler, D., & Jamieson, D. (1989). Temporal resolution in children. *Child Development, 60*, 611-624.

Yathiraj, A., & Vijayalakshmi, C. S. (2005). *Phonemically balanced word list in Kannada.* A test developed at Department of Audiology, AIISH, Mysore.

Zettler, C. M., Sevcik, R. A., Morris, R. D., & Clarkson, M. G. (2008). Comodulation masking release (CMR) in children and the influence of reading status. *Journal of Speech, Language, & Hearing Research, 51,* 772-784.