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Auditory Stream Segregation with Sinusoidally Amplitude Modulated Tones and Noise in Normal Hearing Adults

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Abstract--

Introduction: *The study was aimed to know the effect of temporal and spectral variation in sinusoidally amplitude modulated stimuli resulting in auditory stream segregation using objective listening task procedure.*

Methods: *Thirty normal hearing males and females of age range between 18 to 45 years participated in the study. Three carrier stimuli (1 kHz, 4 kHz and broadband) with low (16Hz) and high modulation frequency (256 Hz) were used in the study. The variation in the modulation frequencies increased up to 4 octaves higher for both these frequencies. In the experiment I two tone delay paradigm (AB sequence) and experiment II single tone delay paradigm (B sequence) was used to find the minimum cumulative delay.*

Results: *The results showed no gender difference in the minimum cumulative delay for both the experiments. The results showed that for lower modulation frequency in the tonal carrier stimuli, a variation of about 3-4 octaves higher is required to form stream segregation. Whereas, for higher modulation frequency with the tonal carrier stimuli, relatively smaller modulation hike of about 1-2 octaves is sufficient to elicit the stream perception. However, no stream segregation was noted when the carrier stimuli was a broadband noise.*

Conclusion: *Hence, from this study it is suggested that the temporal variation in the sinusoidally amplitude modulated stimuli alone could not produce any perceptual stream segregation and requires higher modulation frequency with spectral information to detect the stream segregation.*

Key words--*Auditory stream segregation, sinusoidally amplitude modulated stimuli, carrier stimuli, modulation frequency, broadband noise.*

I. INTRODUCTION

Auditory stream segregation is a phenomenon in which the complex sound mix are segregated and perceived as different stream percept. These perceptual streams are formed majorly by associating or segregating the different sound source where the sounds are derived from.[1] The properties of auditory stream analysis are being studied widely and documented. [1-3] Sequential grouping is one of the properties in which the auditory system groups together the similar sounds with respect to the preceding sounds immediately in time.[1] This grouping or segregation depends on the amount of perceptual differences between the successive sounds. [4]

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In individuals with normal hearing, one of the important cues for segregating or grouping are frequency separations between the two sounds [2-6]. The other important cue for segregating or grouping of sounds that were reported are temporal cues such as rate or temporal envelopes.[1,7] Amplitude modulation in the broad band noise could produce considerable perception of two streams even in the absence of any temporal fine structure cues and spectral cues.[8]

The naturally occurring sounds in the environment provide a combination of the spectral and temporal cues. Sinusoidal amplitude modulation stimuli are one of such stimuli that can provide temporal, spectral cues or both by varying its parameter[9]. The perceptual streams were formed with varying carrier frequency, higher modulation rates and deeper modulation depth[9]. This phenomenon was observed for both the low and high carrier frequencies. They concluded that the spectral cues alone could not explain the extent of stream segregation using sinusoidal amplitude modulated (SAM) stimuli.

Subjective listening paradigm is one of the methods to study the stream segregation in many of these studies. In this paradigm, the subjects were made to decide whether the given token of auditory stimuli has a single or two streams.[3,8,9] The disadvantage of using subjective listening paradigms is that there could be individual biases, [10,11] which could be a subjective inclination to try to segregate or setting a lower criterion for responding to two streams.[12] In the objective listening paradigm, the subject perform temporal gap discrimination task where they have different perceptual thresholds. These differences in the thresholds were used to estimate one or two streams. [12] Identifying the temporal irregularity in the objective paradigm is used to measure the stream segregation.[12-15]

In aim of the study was to estimate the effect of carrier frequency, modulation frequency or just the envelope modulation on stream segregation. Gender differences in stream perception were also studied. The SAM tones and the SAM broad band noise were used to assess the auditory stream segregation in individuals with normal hearing through objective listening paradigm. Knowing the cues involved in stream segregation may help to develop better noise reduction algorithms in hearing aids for individuals with hearing impairment.

II. MATERIAL AND METHODS

Subjects

Thirty adults (15 females, mean age = 27.2 years & 15 males, mean age = 25.6 years) were included in the study. None of the participants had any history or complaints of otological complaints. All the participants underwent pure tone audiometry and had hearing within normal limits (air conduction and bone conduction pure tone thresholds within or equal to 15 dB HL between octave frequencies of 0.25 kHz to 8 kHz).

Generation of stimuli

The SAM signal was generated through AUX Viewer software version 1.0. [16] The SAM generation from pure tone and broad band noise were done based on the previous studies.[9,17] The SAM stimuli with the carrier frequency (f_c) of 1000 Hz, 4000 Hz and a broadband noise with the modulation frequencies (f_{mod}) of 16 Hz were generated. The f_{mod} of 32 Hz, 64 Hz, 128 Hz and 256 Hz with these fc's were generated which were 1, 2, 3 and 4 octaves above the f_{mod} of 16 Hz. Similarly SAM signal with the f_{mod} of 256Hz and 1, 2, 3 and 4 octaves above the f_{mod} of 256 Hz for these f_cs were also generated. A sampling frequency of 44.1 kHz was used for the generation of the SAM. A cosine ramp of 10 msec was used in the generation of each stimuli. The duration of each stimuli was 60 msec. After the generation, the SAM stimuli was aligned in a sequence with various silence period between the two SAM signal using the Adobe Audition software (version 3.0).

Procedure

The procedure for measuring stream segregation with SAM using objective listening task was similar to the experiment by Roberts.[14] There were two experiments conducted to analyse the stream perception. In Experiment I, twelve pairs of SAM stimuli were used and in experiment II, twenty four repeated SAM stimuli were presented. The total duration of the sequence was kept at 2400 msec. The SAM stimuli were introduced in the AB sequence. [15] A standard sequence and a target sequence were used to measure the stream segregation.

Experiment I:

In this experiment, SAM signal of AB sequence was presented. In a particular AB sequence, the f_c and the f_{mod} were constant in the A stimuli. The f_{mod} used in the A stimuli were either 16 Hz or 256 Hz. But, in the B stimuli of the AB sequence, the f_{mod} was varied by one octave above with respect to f_{mod} of A stimuli and the f_c was as that of A stimuli. For example, in a AB sequence, the A stimuli had a f_c of 1000 Hz and the f_{mod} of 16 Hz, then the B stimuli had f_c of 1000 Hz and f_{mod} of 32 Hz (Fig.1). Similarly, the B f_{mod} was varied by either by two or three or four octave above that of f_{mod} of A stimuli. In this example, it was varied either by 64 Hz or 128 Hz or 256 Hz in the B stimuli of AB sequence. If the f_{mod} was 256 Hz for A stimuli then B stimuli had f_{mod} of 512 Hz or 1024 Hz or 2048 Hz or 4096 Hz. This experiment was conducted with all the three f_c i.e. 1000 Hz, 4000 Hz and broad band noise.

In the standard sequence, the gap between the AB cycle in the AB sequence was held constant at 40 msec (Fig.1a). In the target sequence, the B stimuli of the first 6 cycles of AB sequence was separated by an equal interval which is 40 msec as in the standard sequence. From the 7th cycle onwards there was a delay in the time which was denoted as $\Delta T\ was$ introduced.Followed by which, the 8th, 9th and 10th cycle was progressively delayed in an equal steps, i.e $2\Delta T$, $3\Delta T$, and $4\,\Delta T$. For the 11th and the 12th cycle, the delay was held at $4\Delta T$ (Fig.1b). This progressive delay time was introduced in the sequence to make the participant to hear the irregular or arrhythmic sequence [14]. When a delay was introduced in between a AB signal sequence, the silence interval of the next corresponding SAM signal was reduced in order to keep the overall duration constant. The sequence was presented through MATLAB (version R2014a) for the listening experiments. The stimuli was routed through a personal laptop (SONY VAIO model SVE14125) having 64 bit operating system to a calibrated Audiometer (Inventis Piano, Italy). The test sequence was presented diotically to the participants through the HDA 200 headphones. The sequence was presented at 50 dB HL. Two alternative forced choice method (2AFC) was used to find the minimum cumulative delay [14].

The participants were seated comfortably on an arm chair. They were instructed to find which among the two given sequences had an arrhythmic pattern. Ten sequence was given for every participant for their familiarity. The order of the stimulus presentation were randomized across each individual to avoid the order effect.

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The initial cumulative delay ($4\Delta T$) was kept at 32 msec and the step size of delay variation for the cumulative delay was by a factor of 1.189 for each reversal. The minimum cumulative delay (*d*) required for the participant to hear an arrhythmic sequence was obtained. Two down one up procedure was used to find the minimum cumulative delay. The run was terminated after eight reversals and the minimum cumulative delay was calculated by taking the mean of the last six reversals.

Experiment II:

In the experiment II, there was a standard sequence (only B stimuli of AB sequence in the experiment 1) in which SAM stimuli had an equal interval of 40 msec between 24 stimuli (Fig 1c). In the target sequence, the silence between the first 13 cycles of B stimuli (AB sequence of experiment I) of was kept constant at 40 msec. From the 14th SAM signal in the sequence the silence was delayed by a factor of time denoted in ΔTas in the experiment 1. Followed by which, the 16th, 18th and 20th B stimuli was progressively delayed in an equal steps, i.e $2\Delta T$, $3\Delta T$, and $4\Delta T$ similar to that of experiment 1 (Fig 1d). The 22nd and the 24th SAM signal, the delay was held at $4\,\Delta T$. The $4\Delta T$ was considered as minimum cumulative delay (*d*). The minimum cumulative delay (*d*) for the experiment II was measured similar to that of experiment I.

The purpose of conducting two experiments is to know whether the *d* obtained from both the experiments were similar or different. The formation of stream due to the A and B stimuli in the AB sequence may make it difficult for the participants to identify the changes in the gap between the AB cycle. [14]

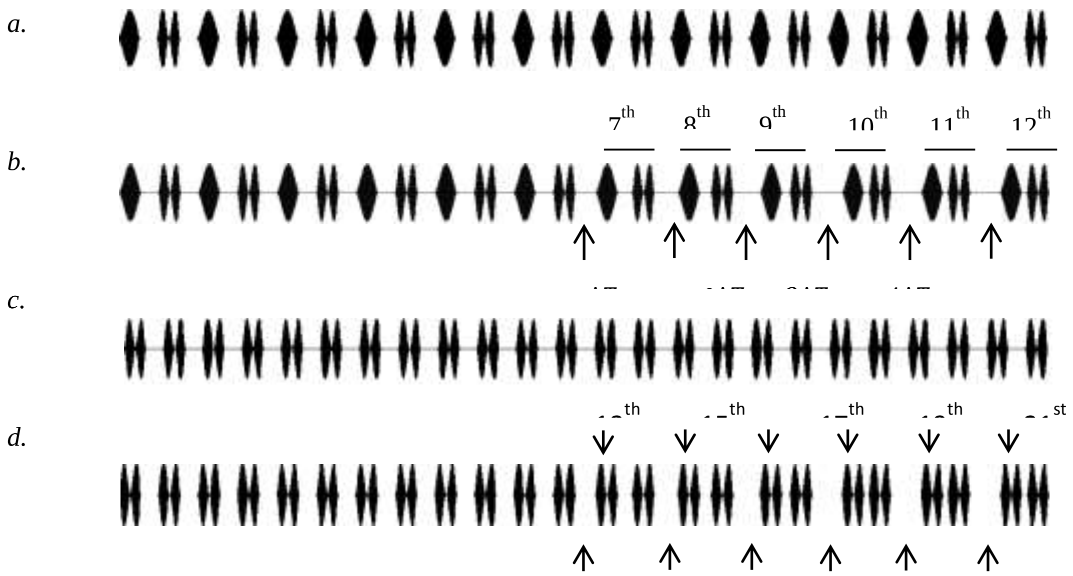

Figure 1

Fig 1a & 1b represents the standard sequence and target sequence of experiment I. Fig 1c & 1d represents the standard sequence and target sequence of experiment II.

III. RESULTS

The minimum cumulative delay (*d)* obtained from the two experiments were tabulated and computed. The analysis of the data were done using the Statistical package of social science (SPSS) Version 20.The mean, median and standard deviation of *d* was obtained for male and female subjects for both the experiments (Table 1 & 2). Shapiro-Wilk test of normality was conducted and found that the dependent variables were not normally distributed ($p < 0.01$). Hence, non- parametric tests were used for the comparison of within and across the groups. Mann-Whitney U test was done to find the difference in the *d* between male and female participants for both the experiments. It was found that there was no significant differences in *d* for any carrier frequencies of 1 kHz, 4 kHz and broadband noises across the difference modulation for the experiment I (Table 3) and in the experiment II (Table 4) between male and female participants. Hence, the data of the two groups were merged for further analysis. The Fig. 2 represents the mean and standard deviation of the *d* for both the experiments for the combined data.

Friedman's test showed a significant main effect in the *d* between the two experiments ($\chi^2(47) = 632.89$, $p < 0.001$, $w = 0.44$). Hence, pair wise comparison was done using Wilcoxon signed rank test to see the difference between the *d* across these different modulation frequencies (32 Hz, 64 Hz, 128 Hz, 256 Hz, 512 Hz, 1024 Hz, 2048 Hz and 4096 Hz) for each of the carrier frequency (1 kHz, 4 kHz and broadband noise).

There was no significant difference found for 32 Hz, 64 Hz and 128 Hz modulation frequencies for 1 kHz carrier frequency between the two experiments. However, there was a significant difference found for modulation frequency of 256 Hz at 1 kHz ($Z=-4.19$, $p< 0.001$, $r = -0.54$) between the two experiments. There was also a significant difference found for 512 Hz ($Z = -2.46$, $p = 0.007$, $r = -0.30$), 1028Hz ($Z = -2.86$, $p = 0.04$, $r = -0.36$), 2048Hz ($Z = -3.23$, $p < 0.001$, $r = -0.41$) and 4096Hz ($Z = -3.65$, $p < 0.001$, $r = -0.47$) with 1 kHz carrier frequency between the two experiments.

There was no significant difference found for 32 Hz, 64 Hz and 128 Hz modulation frequencies for 4 kHz carrier frequency. But, there was a significant difference found for modulation frequency of 256 Hz for 4 kHz carrier frequency ($Z = -2.36$, $p = 0.005$, $r = -0.30$) similar to the 1 kHz carrier frequency. There was also a significant difference found with the modulation frequencies of. 1028 Hz ($Z=-2.40$, $p=0.04$, $r = -0.30$), 2048 Hz ($Z=-2.51$, $p = 0.004$, $r = -0.31$) and 4096Hz ($Z = -3.65$, $p < 0.001$, $r = -0.47$) for 4 kHz carrier frequency between the two experiments. No significant difference was found for 512 Hz modulation frequency at 4 kHz carrier frequency.

There was no significant difference found for any of the eight modulation frequencies for broad band noises ($p > 0.05$).

Table 1: The Mean, Median, Standard Deviation and range of cumulative delay *d* of the male and female subjects for experiment I.

Stimulus	**f_{mod} (B stim)**	**Mean**		**Median**		**S.D.**		**Range**	
		Male	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
1000Hz f_{mod}:16 Hz (A stim)	32	10.0	10.8	8.0	8.0	3.3	6.1	11.2	24.0
	64	13.4	16.2	6.5	13.6	6.5	7.2	24.0	24.0
	128	16.8	13.8	16.0	11.2	7.9	7.3	24.0	24.0
	256	26.9	24.9	32.0	32.0	7.1	8.6	20.8	20.8

1000Hz f_{mod}:256 Hz (A stim)	512	19.6	20.5	16.0	19.2	9.6	5.3	24.0	22.4
	1024	20.5	18.4	19.2	8.5	5.3	8.5	22.4	24.0
	2048	19.7	23.7	19.2	32.0	8.9	10.0	24.0	24.0
	4096	29.3	24.6	22.8	32.0	7.1	8.8	20.8	20.8
4000Hz f_{mod}:16 Hz (A stim)	32	17.1	17.1	11.2	13.6	9.5	10.0	24.0	24.0
	64	13.4	12.7	13.6	16.0	6.7	4.7	24.0	11.2
	128	18.0	18.3	16.0	16.0	10.1	10.9	24.0	24.0
	256	21.2	21.2	19.2	22.8	8.7	8.0	24.0	24.0
	512	10.7	11.0	8.0	8.0	7.0	6.3	24.0	24.0
4000Hz f_{mod}:256 Hz (A stim)	1024	21.1	18.5	11.0	13.6	11.0	10.3	24.0	24.0
	2048	27.1	28.6	32.0	32.0	8.7	12.5	24.0	40.0
	4096	24.9	24.6	32.0	32.0	12.5	10.8	40.0	24.0
BB Noise f_{mod}:16 Hz (A stim)	32	10.5	11.8	8.0	8.0	6.6	8.3	24.0	24.0
	64	8.6	8.2	8.0	8.0	1.5	0.8	5.6	3.2
	128	8.2	11.2	8.0	8.0	0.6	3.8	1.6	14.8
	256	8.5	8.1	8.0	8.0	2.1	0.4	8.0	1.6
	512	8.1	8.3	8.0	8.0	0.4	0.9	1.6	3.2
	1024	8.2	8.7	8.0	8.0	0.6	1.2	1.6	3.2
BB Noise f_{mod}:256 Hz (A stim)	2048	8.3	8.1	8.0	8.0	0.9	0.4	3.2	1.6
	4096	8.2	8.1	8.0	8.0	0.6	0.4	1.6	1.6

Table 2: The Mean, Median, Standard Deviation and range of cumulative delay *d* of the male and female subjects for experiment I.

f_c	f_{mod}	**Mean**		**Median**		**S.D.**		**Range**	
		Male	**Female**	**Male**	**Female**	**Male**	**Female**	**Male**	**Female**
1000Hz	32	12.6	12.6	9.6	13.6	5.8	3.1	18.8	11.2
	64	10.9	13.0	9.6	13.6	3.8	4.6	14.8	14.8
	128	13.6	11.0	13.6	11.2	6.4	3.7	24.0	11.2
	256	12.6	10.9	11.2	11.2	4.2	2.8	14.8	8.0
	512	11.2	13.9	9.6	13.6	3.7	4.3	11.2	11.2
	1024	13.5	12.5	13.6	13.6	3.8	4.2	14.8	11.2

	2048	13.6	11.7	11.2	11.2	5.0	3.7	14.8	11.2
	4096	12.7	13.3	11.2	11.2	5.6	6.1	18.8	24.0
4000Hz	32	12.0	12.0	11.2	11.2	4.2	4.2	14.8	14.8
	64	13.1	13.1	11.2	11.2	4.5	4.5	14.8	14.8
	128	11.8	14.6	11.2	13.6	3.0	5.6	8.0	18.8
	256	11.8	12.5	11.2	11.2	3.4	3.5	11.2	11.2
	512	12.6	11.8	11.2	11.2	4.0	3.6	14.8	11.2
	1024	13.6	12.1	13.6	11.2	4.0	4.1	14.8	11.2
	2048	13.3	12.6	13.6	11.2	4.1	6.1	11.2	24.0
	4096	13.2	11.8	13.6	8.0	4.0	2.8	11.2	8.0
BB Noise	32	8.5	8.5	8.0	8.0	1.2	0.8	3.2	1.6
	64	8.5	9.8	8.0	9.6	0.8	3.7	1.6	14.8
	128	8.5	9.2	8.0	8.0	1.2	2.1	3.2	8.0
	256	9.2	8.8	8.0	8.0	2.9	1.6	11.2	5.6
	512	8.2	8.5	8.0	8.0	0.6	1.0	1.6	3.6
	1024	8.6	8.2	8.0	8.0	0.7	0.6	1.6	1.6
	2048	8.4	8.4	8.0	8.0	0.7	0.9	1.6	3.2
	4096	8.5	8.5	8.0	8.0	0.8	0.8	1.6	1.6

Table 3: The Mann- Whitney U and the significance value of the comparison of minimum cumulative delay *d* between the male and female subjects are for experiment I.

		32Hz	**64Hz**	**128Hz**	**256Hz**	**512Hz**	**1024Hz**	**2048Hz**	**4096Hz**
		16 Hz (A stimuli)				**256 Hz (A stimuli)**			
1 kHz	U	91.5	82.0	79.0	88.0	82	99.0	87.5	99.0
	p	0.37	0.19	0.15	0.29	0.19	0.56	0.29	0.56
4 kHz	U	108.0	99.0	81.5	96.5	99.5	90.0	90.0	88
	p	0.84	0.56	0.19	0.50	0.59	0.36	0.36	0.56
BB noise	U	77.5	85.0	92.0	107.0	104	97.5	107	112.5
	p	0.10	0.19	0.29	0.77	0.58	0.36	0.75	1.0

Table 4: The Mann- Whitney U and the significance value of the comparison of minimum cumulative delay *d* between the male and female subjects for experiment II.

		32Hz	**64Hz**	**128Hz**	**256Hz**	**512Hz**	**1024Hz**	**2048Hz**	**4096Hz**
1 kHz	U	110.0	75.0	83.0	99.0	111.5	105.5	86.5	107.5
	p	0.90	0.12	0.23	0.59	0.96	0.77	0.28	0.83
4 kHz	U	89.5	111.5	86.5	107.5	89.5	111.5	111.0	67.5
	p	0.34	0.96	0.96	0.96	0.38	0.65	0.74	0.93
BB noise	U	97	98	111.5	105.0	105.0	105.0	97.5	105.0
	p	0.93	0.53	0.56	0.96	0.77	0.77	0.53	0.77

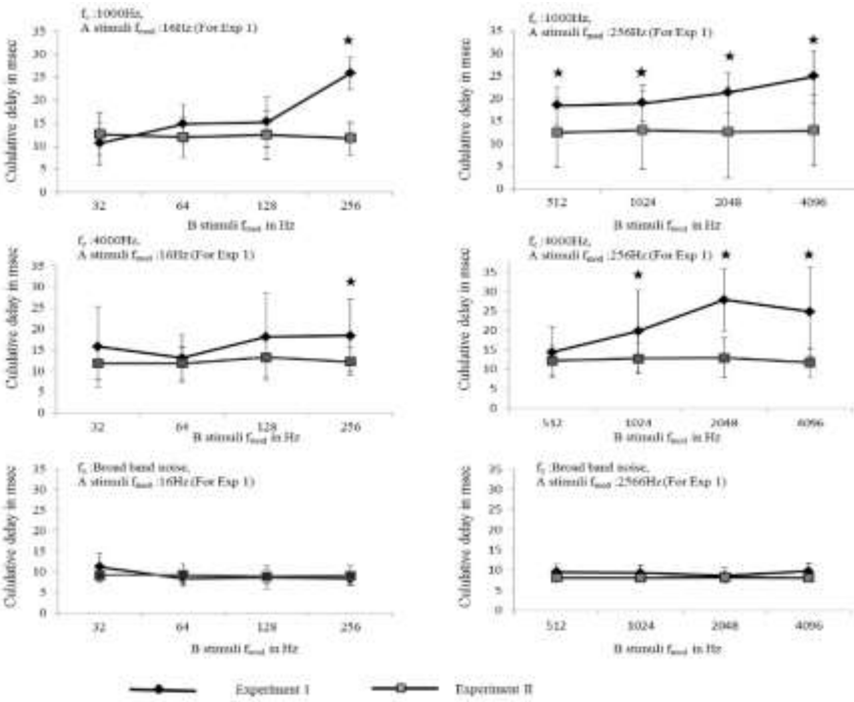

Figure 2

Fig 2: The line graph represents the mean and the error bar represents the standard deviation of the d for experiment I and experiment II (combined data). The cumulative delay is denoted in the Y axis. The B stimuli used in Experiment I as 32Hz, 64 Hz, 128 Hz and 256 Hz in the AB sequence in experiment I and B sequence in experiment II and 512 Hz, 1024 Hz, 2056 Hz and 4096 Hz in the AB sequence in experiment I and B sequence in experiment II are denoted in X-axis.

IV. DISCUSSION

It was found that there was no statistically significant difference in the stream perception of SAM stimuli between the male and female participants. No difference between the genders could be because of the binaural tasks where both the hemispheres were made to work simultaneously rather than working in isolation.[18] The differences seen between the male and female subjects in some auditory processes[19-22] were also attributed to the neuro-anatomical differences where large asymmetry in the cortical organization in the men and varied cognitive lateralization abilities between the genders.[23-25] Most of these experiments were conducted monaurally whereas, the presents study was conducted by presenting the stimuli diotically. This could be one of the reasons for not showing significant difference between the genders. Similar findings were also observed where no difference was noticed between the genders in temporal ordering when the stimulation was binaural [20]. The absence of gender difference may not exclude the possibility of temporal information processed differently between males and females. [26]

There was a significant difference found in the *d* between the two experiments for the modulation frequency of 256Hz of 1 kHz and 4 kHz carrier frequency with the standard modulation frequency of 16 Hz as A stimuli. The *d* was significantly higher in the experiment I. This could be possibly because of the formation of stream of A and B stimuli resulting in the poor judgement in identifying the increased silence between the AB cycles in the experiment I. These results were in accordance with the results of Dollezal[9] except at 4 KHz f_c. The difference in the two studies at 4 KHz f_c could be because of the subject's ability to identify the smaller changes of duration of temporal gaps in the objective listening paradigm.[12]

There was a significant difference found in the *d* between the two experiments for the f_{mod} of B stream i.e. 512 Hz, 1024 Hz, 2048 Hz and 4096 Hz of 1 kHz f_c with f_{mod} of 256 Hz of A stream. There was also a significant difference found in the *d* between the two experiments for f_{mod} of 1024 Hz, 2048 Hz and 4096 Hz of B stream for 4 kHz f_c with f_{mod} of 256 Hz of A stream. The *d* was found to be higher in the experiment I. The present study results were in agreement with the previous studies. [9]

Dollezal[9] developed an excitation model to explain their findings. However, it could not explain the results as the predicted thresholds for obtaining the two stream perception were much higher than what was obtained in their results. Hence, it was concluded that not just the spectral cues but the temporal cues along with the spectral cues in the SAM stimuli was responsible for the stream perception. These observations were consistent with the present study. The results suggest that for the modulation frequencies which are less than 256 Hz, the difference between the two modulation frequencies should be larger for about 3 to 4 octaves in order to obtain the stream segregation irrespective of the carrier frequencies. However, for the higher modulation frequencies above 512 Hz, even the smaller difference of about 1 to 2 octave could result in the stream segregation.

There was no statistical significant difference of the *d* found between the two experiments when the broad band noise was used as carrier stimuli for both the $f_{mod.}$ This was in contradiction to the findings of Grimault[8] where it was found that the modulation in broadband carrier frequency in the absence of spectral or other temporal cues could produce stream perception. However, in the present study, no change in the *d* between the two experiments indicates that the temporal modulation alone in the broad band noise alone could not produce any stream segregation.

The overall results indicates that the stream perception measures were comparable between the subjective and objective listening tasks when the SAM stimuli with tonal carrier frequency was used. However, wide differences were noted when the SAM stimuli with broadband noise was used. This needs to be further investigated.

V. CONCLUSION

The absence of differences in stream percept between the male and female participants with the SAM stimuli may be because of the binaural (diotic) stimulation. The stream percept seen for the SAM with tonal carrier stimuli and not for the carrier stimuli with broad band noise indicate that some amount of spectral cues along with temporal cues are required for stream perception. The stream precepts are better with the higher modulation frequencies as compared to the lower modulation frequencies. The objective listening paradigm results for the stream percept were similar to the subjective listening paradigm for SAM with the tonal carrier stimuli. However, large variations were seen in SAM with the broad band noise.

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