Auditory Masking

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March 2021

PHY0403: Acoustics

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Abstract

Simultaneous and temporal effects of auditory masking are explored in this project. Simultaneous masking of one pure tone by another and its dependence on masker intensity is determined. For a given pure tone masker, with increasing intensity of the masker, frequencies higher than the masker are more effectively masked than frequencies lower than that of the masker. Reasons for this upward shift in masking pattern including theories regarding hypothetical vibrational curves along the basilar membrane, combinational tones arising due to non-linearities in the ear and the presence of subjective overtones are discussed. Forward masking of a tone burst by white noise is conducted. Results show a strong dependence of masker duration and delay time between masker and tone burst on the masking threshold.

Keywords: Acoustics · Masking · Simultaneous masking · temporal masking · pure tones · noise · post masking · masking pattern · upward shift · psychoacoustics

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Auditory Masking

Masking is a very common occurrence in our day-to-day life. Imagine yourself in a busy train station, having a conversation with your friend and in that moment a very loud train passes by. Not only is your voice completely masked by this noise, you now have to speak louder or wait for the train to pass by. In different situations, different types of masking occur. The two different types of masking are – simultaneous and temporal. Simultaneous masking occurs when one sound is made inaudible by another sound when both are played together. Whereas, temporal masking is when one sound is made inaudible by another sound that is played a few moments before or after the sound. In this project, we explore simultaneous masking of one pure tone by another and temporal masking of a tone burst by white noise. In the masking of one pure tone by another, the dependence of the masker intensity on the masking threshold of various frequencies above and below the masker is determined. The independent variable is the masker frequency (1 kHz) and intensity which is varied from 30 dB to 50 dB. The parameter is the test tone frequency varied from 750 Hz to 1500 Hz. The dependent variable is the threshold of audibility of the test tones. In the case of temporal masking, the forward masking of a tone burst by a white noise of 60 dB is explored and the dependence of masker duration on the masking threshold of the tone burst is determined. The independent variable is the white noise of 60 dB whose duration is varied from 1s to 2s and the time interval between the end of the masker and beginning of the tone burst. The dependent variable is the minimum audibility of the tone burst. The constant parameter is the tone burst of 1 kHz of 70 ms duration.

The experimental subjects in this experiment are 4 people between ages 13-51 with normal hearing.

Theory

Dynamics of the Inner Ear

Figure 1. The inner ear.

The inner ear is the innermost part of the ear that houses the cochlea and semi-circular tubes. The cochlea performs the very important function of converting sound pressure vibrations from the outer ear into neural impulses that are passed to the brain via auditory nerves. The semi-circular tubes don't contribute much to hearing. The cochlea is filled with 2 different liquids and surrounded by a bony wall. These 2 liquids are separated by 2 membranes – Reissner's membrane and basilar membrane. The organ of Corti is located on the basilar membrane which contains thousands of tiny hair cells that are connected to nerve fibers. The basilar membrane vibrates in response to the pressure changes in the outer ear. When the cochlea is uncoiled it appears as a tapered cylinder divided into 2 parts by the basilar membrane. At the broader end of the basilar membrane, we have the oval and round windows and at the smaller end is the helicotrema. The stapes vibrate against the oval window and cause ripples in the basilar membrane which are converted to electrical signals by the organ of Corti. The initial frequency analysis takes place in the basilar membrane because of which a sense of pitch is determined. Some sounds also reach the inner ear via bone conduction, i.e., vibration of the skull.

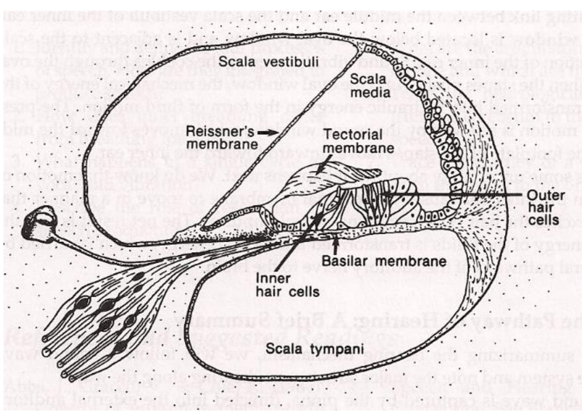


Figure 2. Cross-section of cochlea

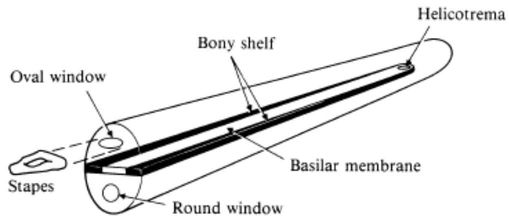


Figure 3.Basilar Membrane

Response of the Basilar membrane

Sounds of different frequencies stimulate different parts of the basilar membrane. Higher frequencies have the greatest amplitude closer to the oval window whereas lower frequencies have the greatest amplitude at the far end closer to the helicotrema. To understand the phenomena of masking and beats, hypothetical curves of vibration or frequency response curves are used.

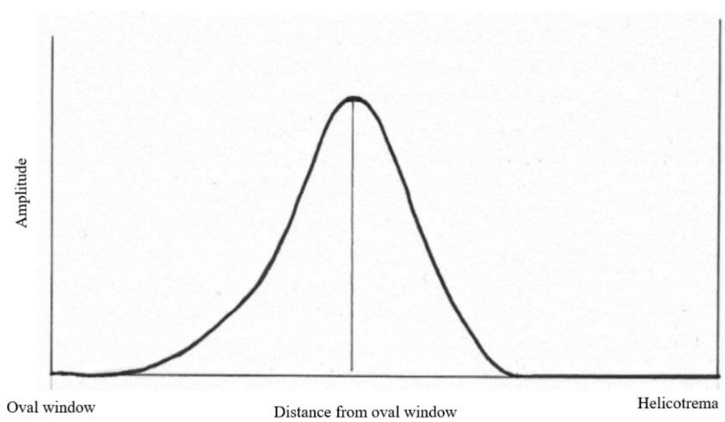


Figure 4. Hypothetical curve of vibration for some pure tone along the basilar membrane

Simultaneous masking of one pure tone by another can be understood with the help of such hypothetical curves. In figure 5, the tone with the higher amplitude is the masker. Tones a, b and c are secondary (test) tones of the same frequency but different levels that may or may not be getting masked by the masker tone. Tone a's maxima is high enough to be heard along with the masker and Tone c's envelope is completed covered by the masker's envelope. Tone c's envelope is *just* covered by the masker and at this level of tone c, the pitch of both the pure tones will be perceived separately by the human ear. Note that if the test tone frequency falls within the critical bandwidth of the masker tone, beats will be audible. The phenomenon of beats is different from masking as the person will hear the pitch of both the tones alternatively (like a wobble) and no information about masking in this beats region can be determined.

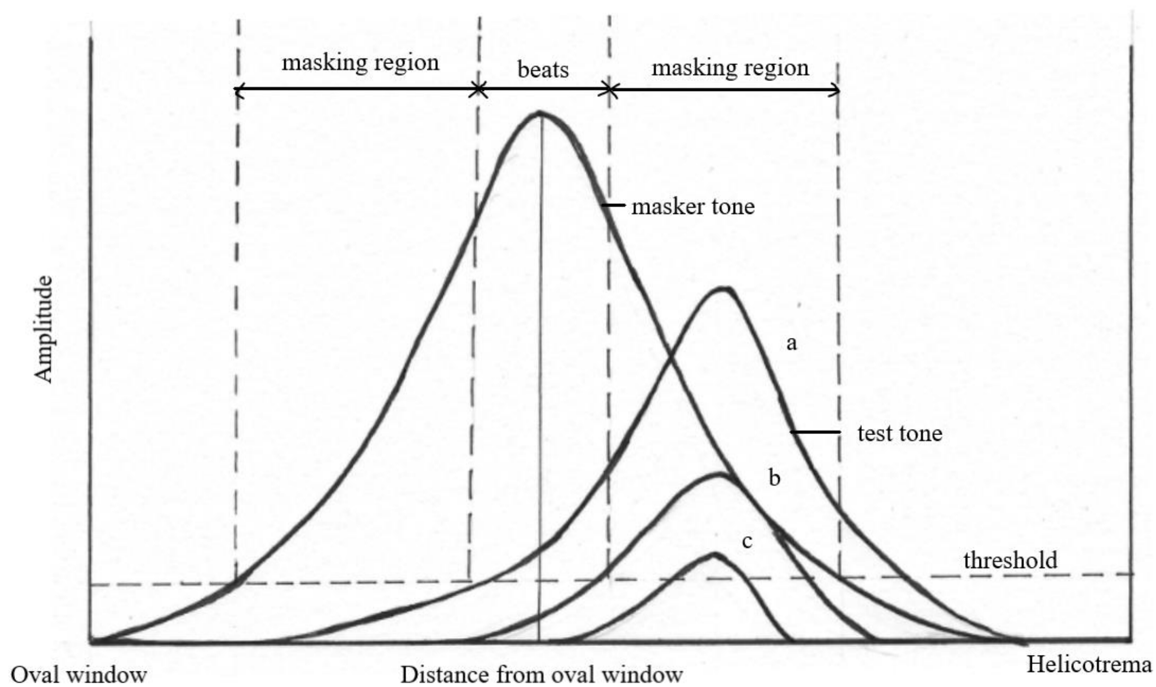


Figure 5. Hypothetical curves of vibration for two pure tones along the basilar membrane

Experiment

Apparatus

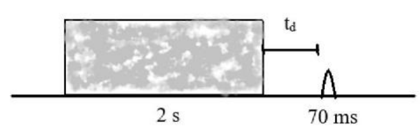
The experiment was conducted at home using the Audacity Software on a laptop. Generation of tones and its analysis was done using the same. Standard AKG earphones were used for the experiment. Th experiment was conducted on 4-5 experimental subjects in a relatively noise-free home setting.

Procedure

Simultaneous masking of one pure tone by another

- A pure tone of 1kHz was generated using Audacity software and kept constant at a sound level of 30 dB.
- Test tones of frequencies 750 Hz, 800 Hz, 900 Hz … and so on were generated and were played simultaneously with the 1kHz tone.
- The level at which the subject was just able to hear an additional tone was recorded as the threshold for that particular test tone.
- This procedure was followed for sound levels of 40 dB and 50 dB as well.

Post-masking of pure tone by white noise



- A white noise was generated for a duration of 2 s at a sound level of 60 dB on Audacity.
- After time gaps of 1ms, 2ms, 5ms, 10ms…, a 1kHz tone burst of 0.07s was played.
- The level at which the subject was just able to detect the tone burst were recorded as the threshold.
- Furthermore, the same experiment was conducted for a white noise of duration 1 s to see the dependence of masking on masker duration.

Observations

I. Simultaneous masking of one pure tone by another

Table 1. Level of test tones masked by 1 kHz pure tone at 30 dB

Test tone frequencies (Hz)		750	800	900	950	997[1]	1050	1100	1200	1300	1400	1500
Test tone level (dB SPL)	Person 1 (13 years)	3	6	6	6	13	3	1	1	1	1	1
	Person 2 (20 years)	3	4	8	12	13	9	9	6	4	2	1
	Person 3 (45 years)	5	6	8	5	13	5	3	1	1	1	1
	Person 4 (51 years)	6	2	10	12	13	7	3	1	1	1	1
	Average	4.25	4.5	8	8.75	13	6	4	2.25	1.75	1.25	1
	Standard Deviation	1.299	1.658	1.414	3.269	0	2.236	3	2.165	1.299	0.433	0

Table 2. Level of test tones masked by 1 kHz pure tone at 40 dB

Test tone frequencies (Hz)		750	800	900	950	997	1050	1100	1200	1300	1400	1500
Test tone level (dB SPL)	Person 1 (13 years)	8	9.75	15.25	17.75	23	17.075	12.75	10.75	9.75	5.75	5.5
	Person 2 (20 years)	6	7	13	17	23	19.3	11	12	9	9	10
	Person 3 (45 years)	8	12	17	19	23	15	12	10	7	5	4
	Person 4 (51 years)	10	8	14	17	23	16	13	8	10	3	1
	Average	8	9.75	15.25	17.75	23	17.075	12.75	10.75	9.75	5.75	5.5
	Standard Deviation	1.4142	2.277	1.785	0.829	0	1.678	1.479	1.920	2.165	2.165	3.354

[1] Note that at 997 Hz, the subject reports that they can hear beats; this isn't the phenomena of masking and is thus ignored. The test tone level recorded for this frequency is just a 'filler' or dummy value and has absolutely no contribution to our final results.

Table 3. Level of test tones masked by 1 kHz pure tone at 50 dB

Test tone frequencies (Hz)		750	800	900	950	997	1050	1100	1200	1300	1400	1500
Test tone level (dB SPL)	Person 1 (13 years)	11	15	22	32	33	28	24	26	27	27	27
	Person 2 (20 years)	12	16	19	27	33	27	28	27	25	29	30
	Person 3 (45 years)	11	13	21	25	33	26	23	21	21	24	29
	Person 4 (51 years)	14	14	22	30	33	27	24	21	19	16	19
	Average	12	14.5	21	28.5	33	27	24.75	23.75	23	24	26.25
	Standard Deviation	1.224	1.118	1.224	2.692	0	0.707	1.920	2.772	3.162	4.949	4.322

II. Post-masking of pure tone by white noise

Tone burst is a 70 ms sound of 1000 Hz pure tone. The ‘delay time’ is the time between the end of the masker and the end of the tone burst.

Table 4. Level of tone burst masked by 2s long white noise (masker)

Delay time (t_d) (ms)		1	2	5	10	20	30	50	100	200
Tone burst level (dB SPL)	Person 1 (13 years)	14	14	13	13	12	10	12	5	4
	Person 2 (20 years)	14	18	17	16	13	12	12	7	2
	Person 3 (51 years)	20	18	16	15	15	14	15	9	6
	Average	16	16.666	15.333	14.666	13.333	12	13	7	4
	Standard Deviation	2.828	1.885	1.699	1.247	1.247	1.632	1.414	1.632	1.632

Table 5. Level of tone burst masked by 1s long white noise (masker)

Delay time (t_d) (ms)		1	2	5	10	20	30	50	100	200
Tone burst level (dB SPL)	Person 1 (13 years)	14	11	11	10	10	10	5	5	4
	Person 2 (20 years)	14	15	14	13	12	11	8	5	4
	Person 3 (51 years)	20	16	15	14	13	12	11	6	3
	Person 4 (19 years)	11	11	10	9	8	7	7	5	4
	Average	14.75	13.25	12.5	11.5	10.75	10	7.75	5.25	3.75
	Standard Deviation	3.269	2.277	2.061	2.061	1.920	1.870	2.165	0.433	0.433

Graphs

I. Simultaneous masking one tone by another

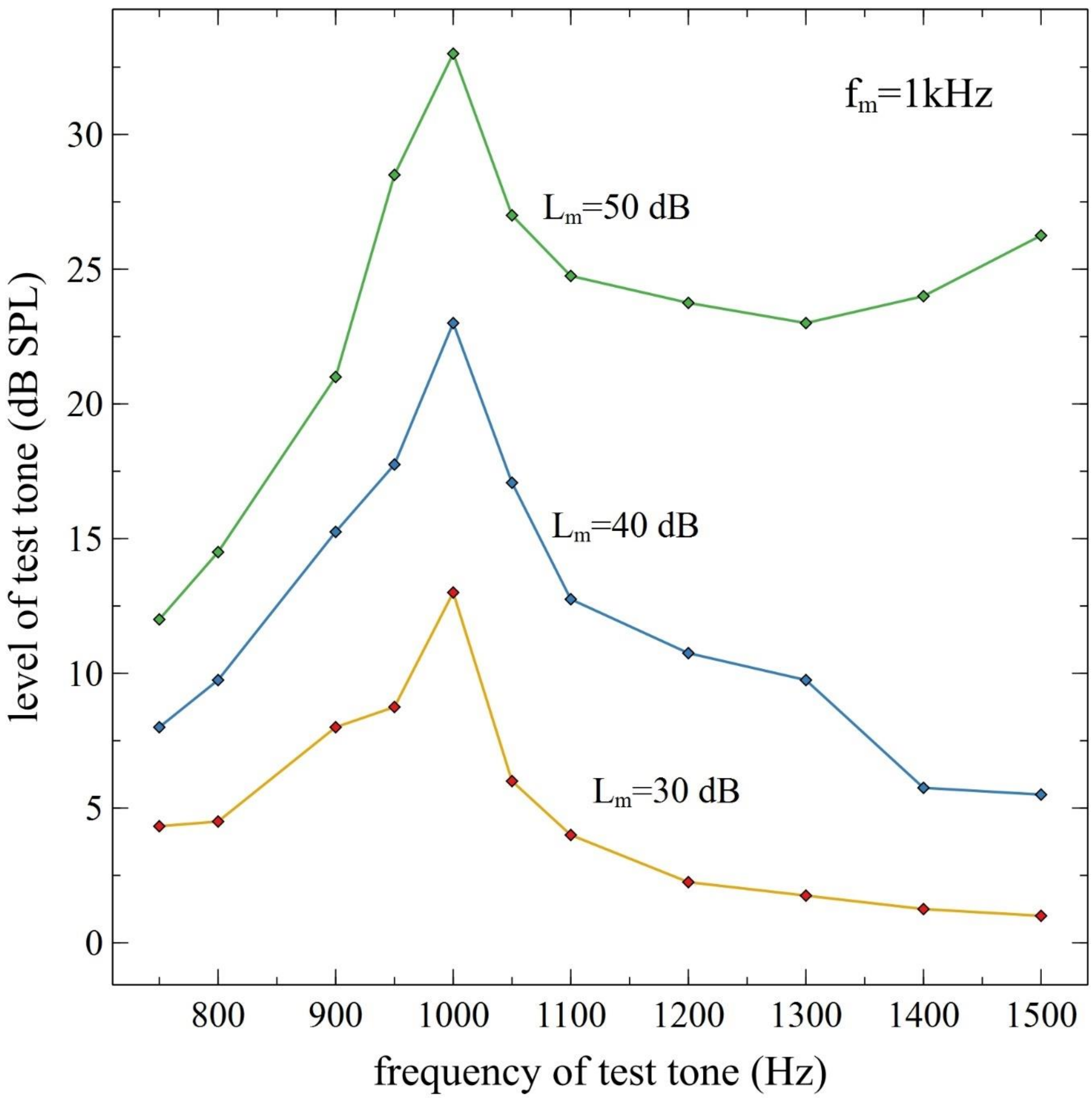


Figure 6. Level of test tones masked by pure tone of 1 kHz of different sound levels for various frequencies of test tones.

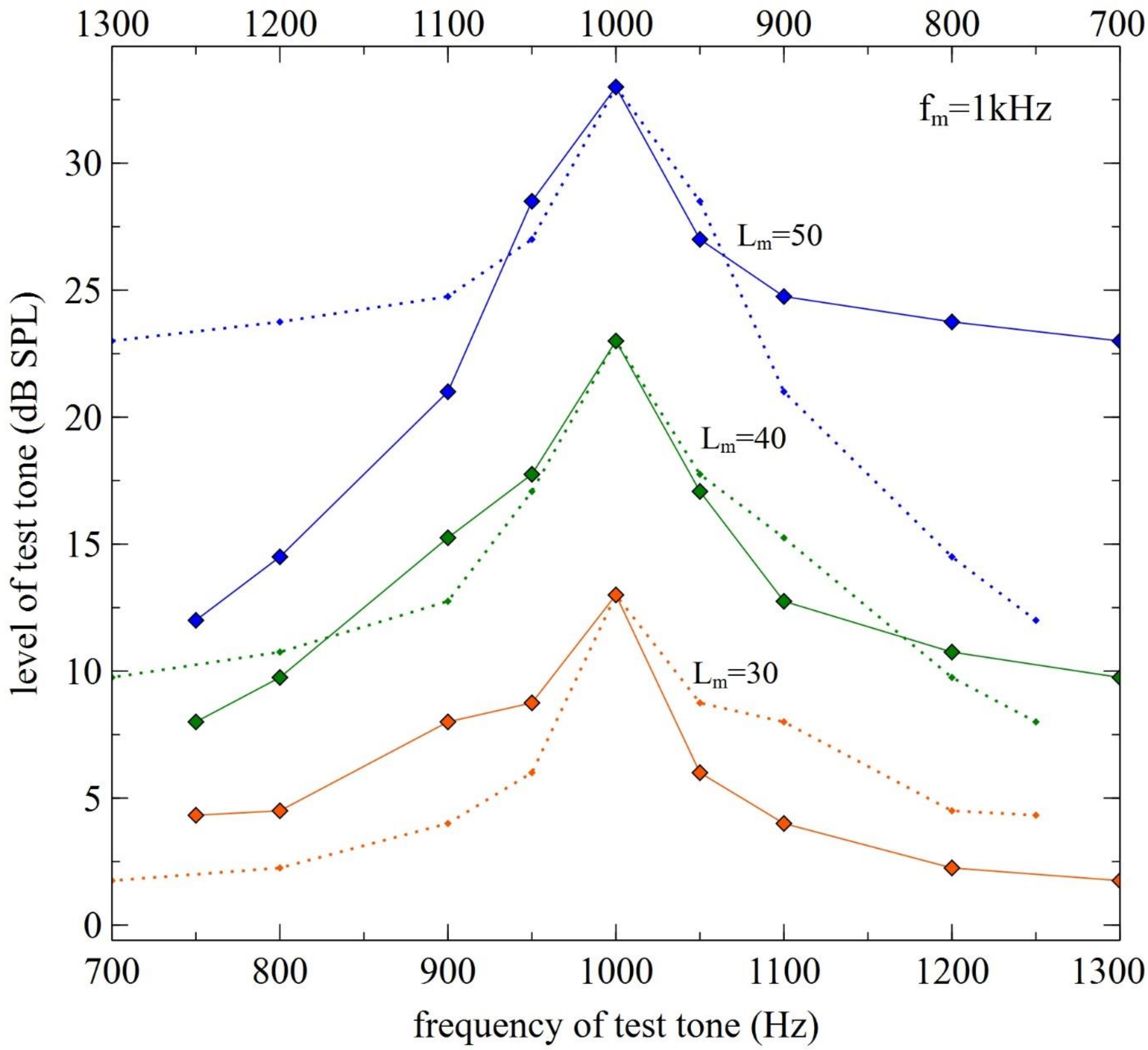


Figure 7. Solid lines are the level of test tones of pure tones of varying frequencies masked by a pure tone of 1 kHz (masker) of different levels. Dotted lines are the same data points as the solid line plotted in an inverted frequency scale (upper abscissa).

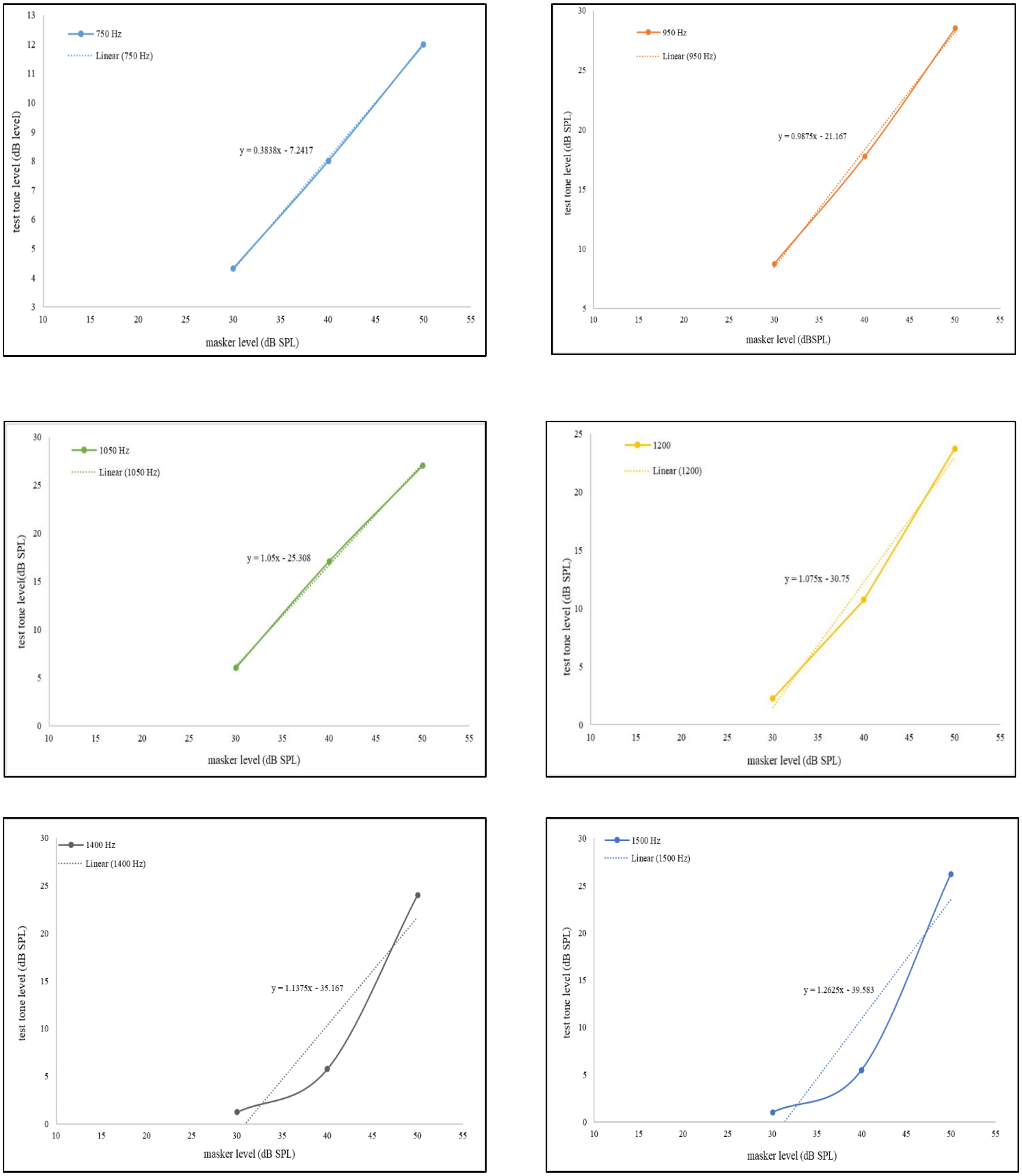


Figure 8. Plots of test tone level and masker level for individual test tone frequencies to the noticeable upward shift in masking of higher frequency test tones with increasing masker level.

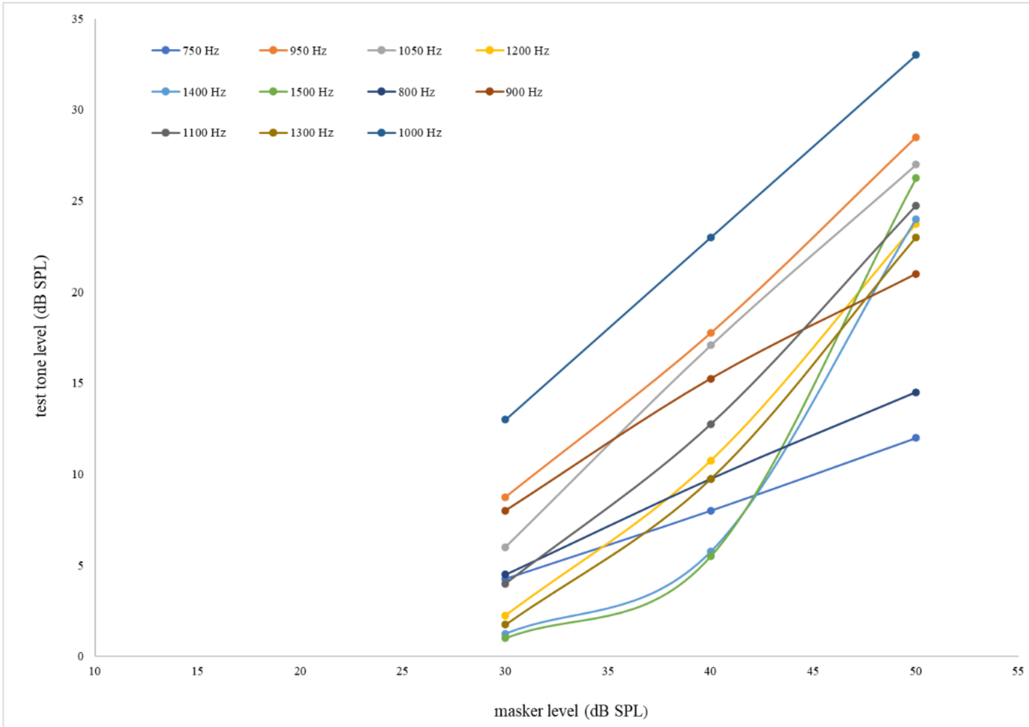


Figure 9. Level of the test tones as a function of masker levels. The parameter here is the frequency of the test tones.

II. Temporal masking of pure tone by white noise

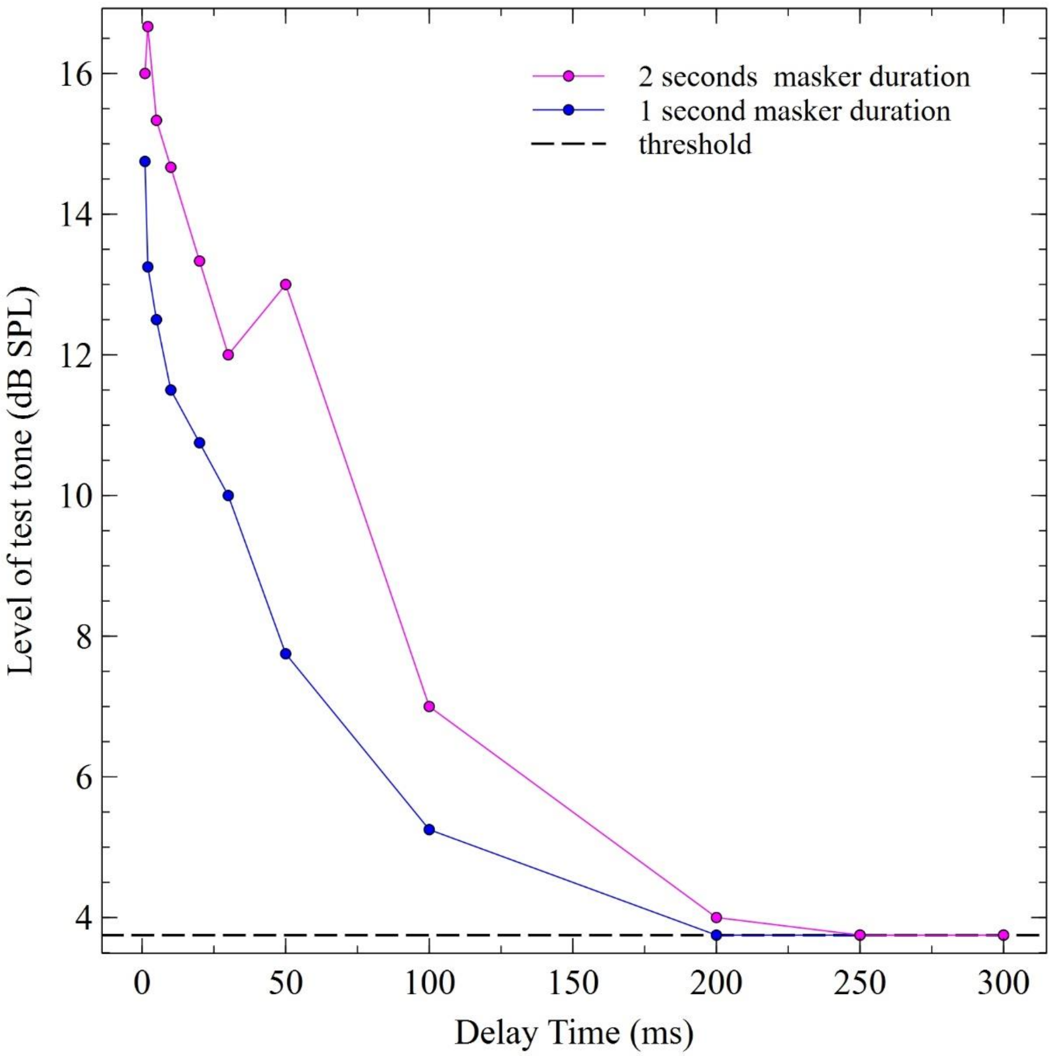


Figure 10. Masking of tone burst as a function of duration of the masker. The curves for different masker durations are different indicating that forward masking depends on the masker duration.

Error Analysis

I. Simultaneous masking of one pure tone by another

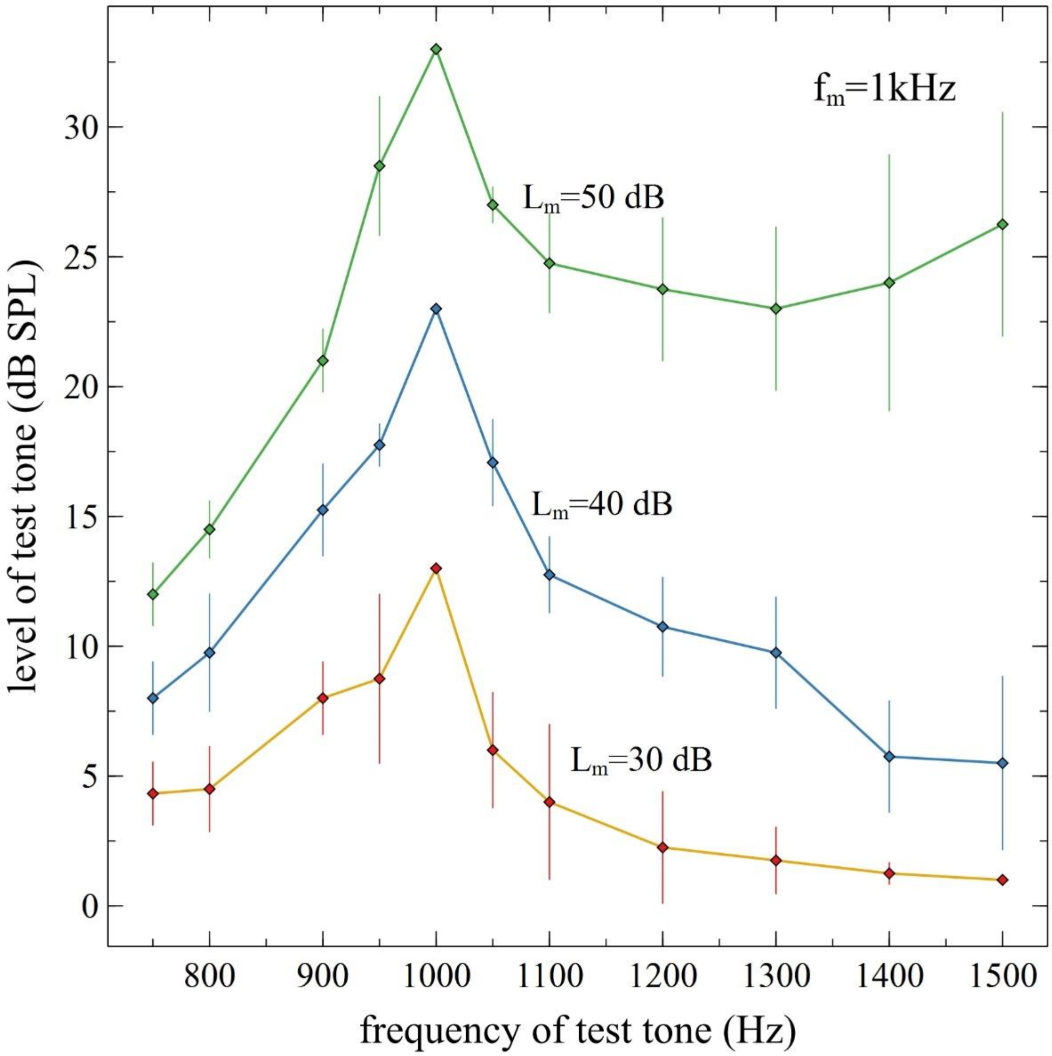


Figure 11. Level of test tones masked by pure tone of 1 kHz of different levels as a function of frequency of test tones with error bars signifying the standard deviation of the data points.

Sources of Error

- Noise: A noisy environment can raise the threshold of audibility for the test sounds causing the subject to inaccurately report the minimum audible level of the test tone in the presence of the masker.
- Average quality earphones: Lack of a professional grade calibrated microphone.

II. Temporal masking of pure tone with white noise

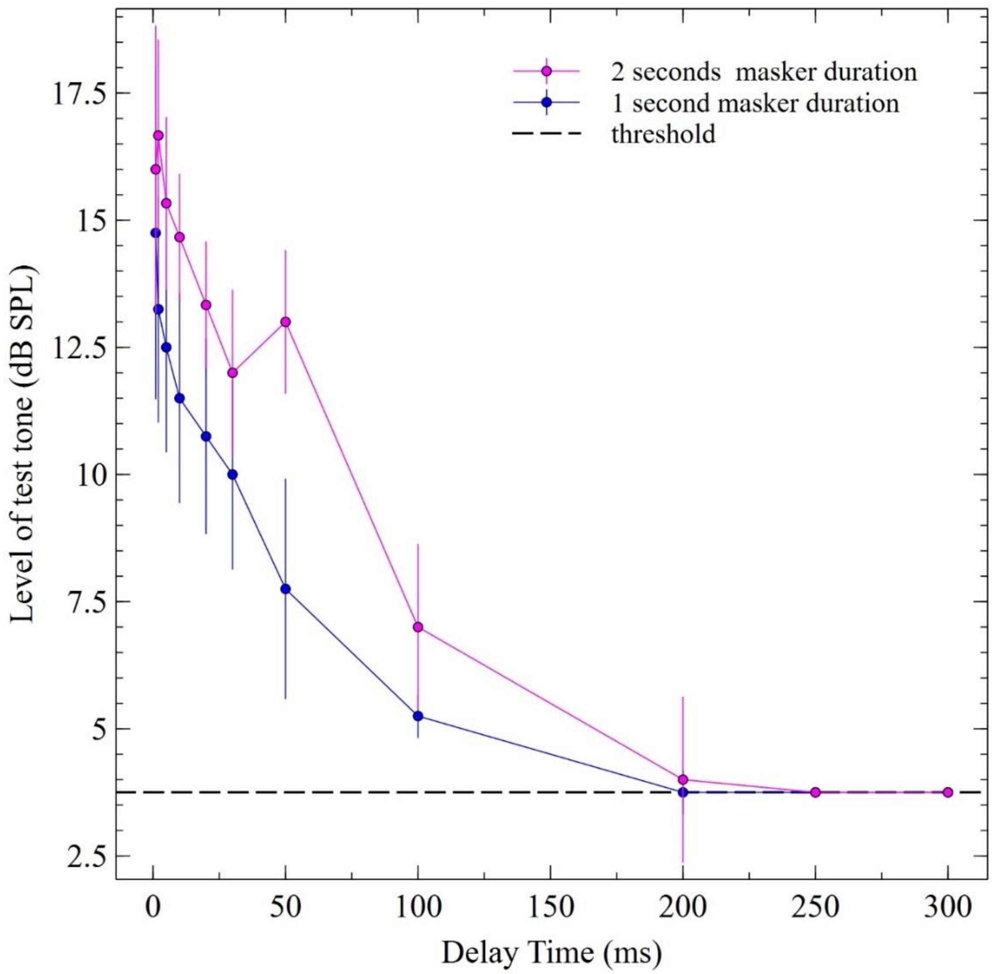


Figure 12. Level of tone burst masked by white noise of different durations as a function of delay time with error bars signifying the standard deviation of the data points.

Sources of Error

- Human bias: Hearing sensitivity and the ability to hear sounds varies greatly among subjects. It depends on the age and hearing impair of the subject. In this experiment, various subjects from different age groups were taken to plot the average of the data points.
- Fatigue: Constantly listening to a 60 dB white noise for all the readings could tire the hair cells in the subject and create inconsistent readings. To reduce the possibility of this error, the subject was called for the experiment in 2 sittings.

Results and Discussion

In simultaneous masking of one pure tone by another, we see that at higher levels of masker, pure tones of frequency higher than the masker are more effectively masked than tones lower in pitch than the masker. This is known as the upward shift in masking pattern. The reverse happens with decreasing intensity of the masker tone; tones of frequencies lower than the masker are masked more effectively than those with frequency higher than the masker tone.

This shift may not be clearly visible to the reader in Figure 6 which is why the same data points are plotted with an inverted frequency scale (upper abscissa) in Figure 7. For masker intensity of 50 dB, the dotted line is much below the solid line showing that the curve becomes flatter as the frequency of the test tones exceeds the masker tone. For 40 dB, the solid line and the dotted line nearly overlap which shows that the curve is symmetric about 1 kHz. For 30 dB, the dotted line lies much above the solid line showing that the curve is steeper after the 1 kHz mark.

This effect is illustrated more clearly in Figure 8 where for each test tone, graphs with the level of test tone as the ordinate and masker level as the abscissa is plotted. The greater the frequency of the test tone, the more the slope of the curve deviates from 1 (45°). For 1500 Hz test tone, the slope is 1.26 which means that for every 1 dB increase in the masker level, the test tone level increases by 1.26 dB. For test tone frequencies closest to 1 kHz (masker tone), the slope is nearly 1 implying that for every 1 dB increment in the masker level the increment in the test tone level is also 1 dB. For lower frequencies like 750 Hz, the curve doesn't suddenly become steeper at higher levels of masker and stays linear for the entire range of masker levels.

One possible reason for this effect could be the gradual decrease in the slope of the hypothetical vibration curves towards the oval window/ stapes at higher intensities of the sound.

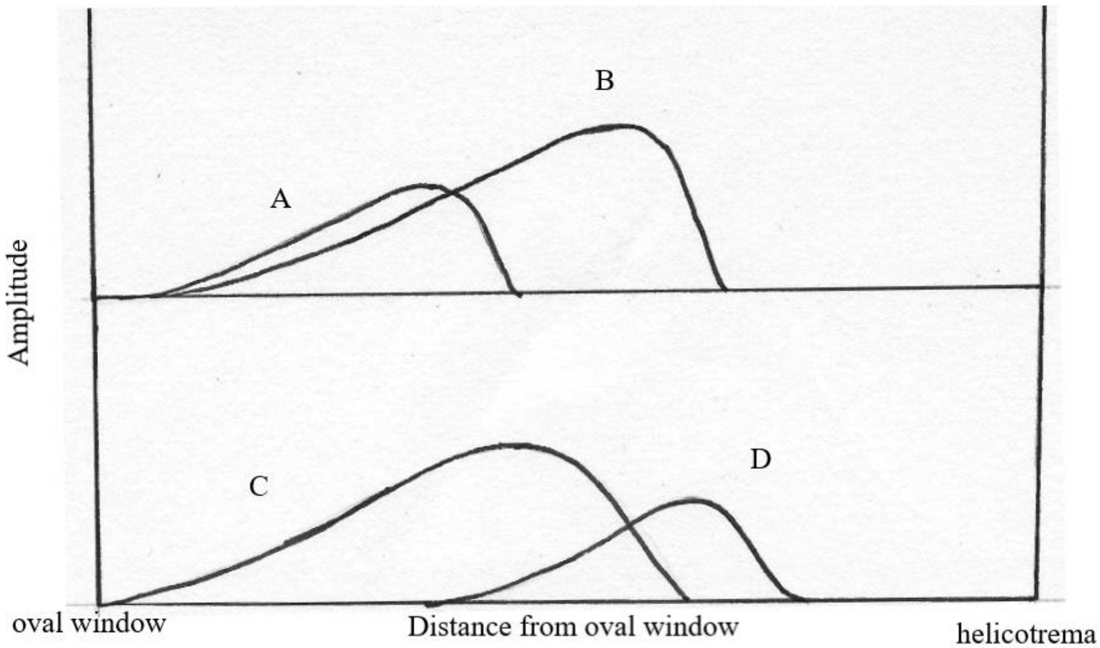


Figure 13. Masking of pure tones by other pure tones of high intensity could possibly be due to basilar membrane mechanics

In Figure 13, Tone B overlaps Tone A (of higher frequency) completely whereas tone C despite being of higher intensity doesn't appreciably overlap the envelope of tone D (of lower frequency). At lower intensities, the curve is confined to a local region. This is only a probable reason behind the upward shift and theres no way of determining the actual basilar membrane mechanics on account of inaccesibility of the inner ear except from extrapolating the mechanics from experiments like this.

Another topic of discussion important in the case of simultaneous masking of one pure tone by another is the audibility of combinations tones that arise due to non-linearities in the human ear. When two pure tones f_1 and f_2 ($f_1 < f_2$) are played together they give rise to tones with pitches that don't correspond to f_1 or f_2 but to frequencies such as $f_1 - f_2$, $2f_1 - f_2$,…, $f_1 – k(f_2 – f_1)$. When a subject is made to hear two pure tones simultaneously, the pitch of the combination tone would be detected before the pitch of the test tone. In this masking experiment, the general procedure involves directing the subject to report the detection of 'anything' rather than recognizing the pitch of the test tone. Therefore, the subject would incorrectly report hearing the thresold of audibility of the combination tone rather than the masked test tone. This error can be eliminated if the subject is made to recognize the pitch of the tone, however, that is a rather tedious task for an inexperienced listener. The audibility of the cubic difference tone $2f_1 - f_2$ depends on the rartio of f_1/ f_2 whereas the dependence of the quadratic difference doesn't depend much on the ratio f_1/ f_2. Whatever the case be, the intensities of the primary tones must be sufficiently loud to detect these combination tones. In various experiments in the past, these combination tones have beee masked by introducing a low-pass noise to the masker tone f_1. So, although combination tones do lower the threshold of masking of pure tones, it's a less likely reason for the upward shift as there are only specific ranges of frequency and intensity over which they are heard. Similarly another phenomenon known as aural harnomics arising from non-linearities in the ear has been suggested as a probably reason for the upward shift in masking patterns. These overtones, however are only hear at very high intensity of pure tones and don't contribute significantly to the upward shift.

In the curve obtained for temporal masking in Figure 10. Masking of tone burst as a function of duration of the masker.Figure 10, we see that with increasing interval between the tone burst and masker, the masking of the tone burst decreases. For time delay of 1 ms- 50 ms, the masking is greatest and for a delay of 200 ms, there is little to no masking. For time delay longer than 200 ms, the masker has no effect on the tone burst and can be heard at its minimum audible level just as it does in the absense of any additional stimuli. One reason why this decay is observed may be due to temporary threshold shift (TTS). Recently stimulated hair cells are not as sensitive as fully rested hair cells and may need some recovery time to detect any sound.

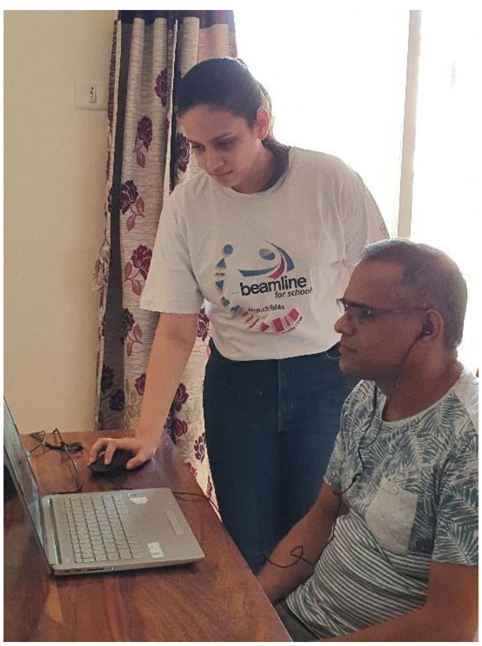
When the duration of the masker is reduced from 2 s to 1 s, the decay is much steeper for the 1 s masker as compared to the 2 s masker. Although the curves obtained are only for two different masker durations, the data points are the average of 3 experimental subjects and therefore, our results are conclusive in showing that there is a strong dependance of masker duration on forward masking.

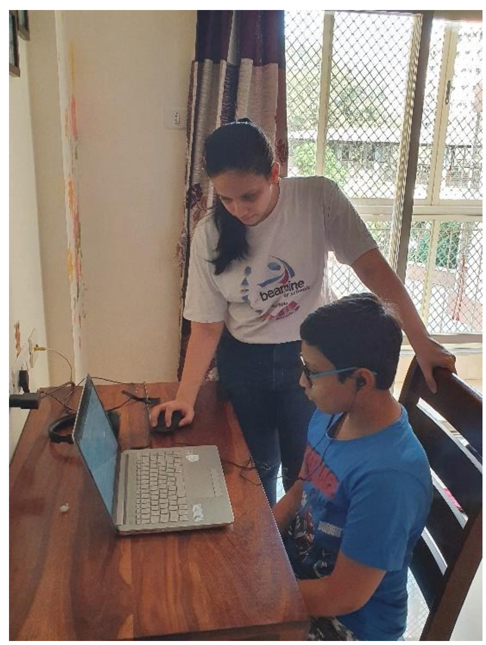
Applications

- Auditory masking is used in tinnitus maskers which are devices used to cover up annoying ringing tones. They generate white noise through a generator, which can be placed in/above the ear or somewhere else in the environment.
- Masking is used in different kinds of audiometry, for example pure tone audiometry which is a hearing test used to identify the hearing threshold level. A hearing test evaluates the sensitivity of a person's hearing and is done using an audiometer.
- MP3 audio compression: masking is very important in music and is used in compressing MP3 audio files. Say for example, in a musical performance a loud orchestra is playing that masks the softer instruments. These inaudible sounds can be removed in in order to reduce the file size and increase its efficiency.

Conclusion

In the simultaneous masking of one tone by another, the threshold of masking of higher frequencies increases with increasing masker tone intensities. The masking pattern of a pure tone purely depends on the spread of the vibration curves of the basilar membrane towards the stapes. Other theories involving aural harmonics and difference tones suggested in many papers in the past don’t conclusively explain the upward shift for then entire range of test tone frequencies. Forward masking of a click or tone burst by a white noise masker shows strong dependence on masker duration and time delay between the tone and the masker. The lower sensitivity of recently stimulated hair cells can describe the decrease in masking threshold of the test tone as the delay time is increase and the masker duration is decreased.





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