THE SAHLGRENSKA ACADEMY
INSTITUTE OF MEDICINE

THE IMPORTANCE OF LOW FREQUENCY MASKING ON AUDITORY PERCEPTION

Literature Review

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REPORT NO 4:2017

FROM THE UNIT FOR OCCUPATIONAL & ENVIRONMENTAL MEDICINE IN GOTHENBURG

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Summary

In this review, previous studies on the effect of the low frequency masking on speech comprehension are presented. First the theoretical background of masking focusing on low frequency masking of speech is presented. Previous studies and experiments that analysed low frequency masking patterns are reviewed and used as baseline knowledge for further investigation on speech intelligibility for normal hearing and hearing impaired people. Furthermore the combined effect of the reverberation and noise on speech intelligibility, before and after acoustical treatments of different rooms, was reviewed and presented in this report.

The review showed that low frequency noise is an efficient masker of speech and lead to reduce speech intelligibility because of the increase of masking of higher frequencies (upward spread of masking) which is strongly dependent on the level and frequency of the masker. Especially maskers up to 350 Hz at sound pressure levels that normally occur at public spaces (offices, schools etc.) were indicated as efficient maskers of speech with the masking effect to increase with the increase of low frequency components in the masking noise.

Hearing impaired people are strongly affected by the combined effect of reverberation and noise which makes it difficult to communicate in noisy environments. Spaces with poor acoustic properties increase the masking of higher frequencies (especially in speech) by lower frequency speech components. Finally, the importance of a good acoustic environment for speech intelligibility especially for vulnerable groups such as young and old, non native listeners and people with hearing impairments, was documented and presented.

Introduction

Noise in schools, hospitals, offices and other communication areas can decrease the comfort and speech intelligibility affecting the occupants' concentration and communication especially among hearing impaired listeners, young and old listeners and non native listeners. The human hearing system has an exceptional ability to identify process and interpret sounds and noises. However in many acoustic environments, not even good auditory skills are enough for the listener to obtain correct acoustical information. Fundamental conditions for satisfactory listening conditions are good signal to noise ratios and low influence of late reflections from the room often assessed as short reverberation time. However, increasing the understanding of masking and low frequency masking in particular may help improve the sound environment and increase speech intelligibility.

A common acoustic advice given by acousticians and technical consultants is to strive for a rather flat reverberation curve. In this way, the masking of high frequency sounds by low frequencies will be reduced. The scientific background is however scarce. The scope of this paper is to present a literature review regarding low frequency absorption and the effect on speech comprehension.

Method

The present review was based upon studies that were focused on the low-frequency masking effect on normal hearing and hearing impaired listeners aiming a comfortable acoustic environment for everyone. The review was initiated and financed by Saint-Gobain Ecophon with the aim to investigate and provide the amount of existing studies on low-frequency masking effects and low-frequency absorption. Carsten Svensson and Erling Nilsson were contact persons. The review was conducted by Stamatina Kalafata and Kerstin Persson Waye at the Sound Environment and Health research unit at the department of Occupational and Environmental Medicine, Gothenburg University and the authors are independently responsible for the content and conclusions of the report.

Search strategy

The following databases were used:

- PubMed
- Scopus
- Gothenburg University library
- Chalmers University of Technology library
- Google scholar

The search strategy included keywords and free-text words and among a large number of studies the ones accepted were scientific articles, technical reports, independent studies and books.

The basic search was based on the words and combination of words in Table 1.

Table 1: Keywords used for the basic search.

	Database	
	Scopus	**PubMed**
Listen*	9	36
Voice*	0	0
Vocal*	0	0
Masking*	63	165
Auditory*	40	67
Speech*	9	25
Processing*	12	27
Hear*	35	74
Noise*	34	111
Sound*	13	32
Human*	43	29
	Database	
	Scopus	**PubMed**
Auditory -Masking	37	64
Speech -Processing	4	6
Hear -Sound	10	15
Auditory -Processing	6	6
Speech -Masking	7	23
Processing -Masking	10	19

Keeping constantly as main keywords low* freq* mask*, a different secondary word or phrase was used in the search for useful studies. Many of the resulting articles and studies were the same for the different keywords and after the first check (by title and/or abstract) only 20 of them were relevant.

The next step was to search among the references of the useful studies and further search in the libraries. The GU and Chalmers libraries were also used for the search of useful books for the theoretical parts and to obtain the full text of some of the studies. Also Google scholar was used for citations and further search.

In total, 56 articles were gathered for more detailed reviewing and resulted in 39 articles, reports and books finally being included. For the theoretical part and for some useful figures, approximately 10 books (in electronic form from the libraries) were reviewed using the same keywords.

Inclusion criteria

The results from the keyword searching gave a wide range of studies about low-frequency noise, masking of auditory information and hearing impairment. The articles fulfilling the inclusion criteria were focused on the effects of masking on auditory information especially by low frequencies, perception and intelligibility of speech, low-frequency absorption and comfortable acoustic environment for normal hearing and hearing impaired listeners. All the studies were focused on the low-frequency effect on humans without any date restrictions. The 56 useful studies were published during the period 1924-2015. Multiple publications with similar topics were identified, checked and only the most relevant to this review were accepted.

Background theory

Auditory masking

Everyday life is full of noises, sounds and speech. The human ear has the ability to hear two sounds at the same time and respond selectively to one sound or another. But sometimes one sound is not audible because of a presence of another sound. This interference is called auditory masking and it is critical for the understanding of speech. According to the American standard acoustical terminology [1], masking is defined as ''the amount by which the threshold of audibility of a sound is raised by the presence of another sound and it is expressed in decibels (dB)''. The masking occurs if the ear is not able to separate the frequencies of the masker and the test sound. Masking can be defined as the limits of frequency selectivity of the auditory system. This assumption can be applied for both pure tones and complex sounds, like speech. One way to define the auditory masking is to measure the difference, in decibels, of the hearing threshold of the listener in quiet and the masked threshold.

The analysis of speech

Speech is a sound with temporal structure and its energy is constantly shifting between loud and faint sounds, varying in intensity and frequency. Generally, speech can be divided into voiced and unvoiced sounds depending on their mode of excitation. When the air from the lungs set the vocal cords into a quasi-periodic vibration, the voiced segments are produced, e.g. vowels and some consonants, while the sounds produced without a vocal cords vibration are the unvoiced segments, e.g. consonants [2]. In Fig. 1, an example of the spectrogram and the time-domain waveform of the Finnish word ''kaksi'' (two) are presented in order to understand the frequency and energy differences.

It is shown that the energy of the vowels is higher in amplitude and it is distributed in lower frequencies than the consonants. This information is obtained by the darker gray-levels of the spectrogram that show the higher amount of energy. The unvoiced consonants, e.g. 'k', have no energy while the voiced consonant 's' contains high amounts of energy basically distributed in higher frequencies. In general, vowels can be analyzed as segments of low frequencies with a fundamental frequency at around 100-200 Hz while voiced consonants are distributed in higher frequencies and are of rather high amplitude compared to unvoiced consonants.

Miller in 1947 [4], presented a long time average distribution of the speech energy based on previous experiments and research [5, 6]. Fig. 2 shows the graph as an attempt of a more general understanding of the energy distribution of the speech.

The results for the upper curve were obtained from an experiment which was performed among seven American native speaking males, speaking in a conventional voice at 18 inches (≈46 cm) distance from the microphone in 1940 [6] while the two lower curves were obtained in 2012 [34].

In terms of a long-time average, one can generally consider speech as a broadband noise with most of the power carried by frequencies below 1000 Hz. The masking of speech depends on the intensity of the masker stimulus relative to the intensity of the speech, the acoustic spectrum of the masker and its temporal continuity [4].

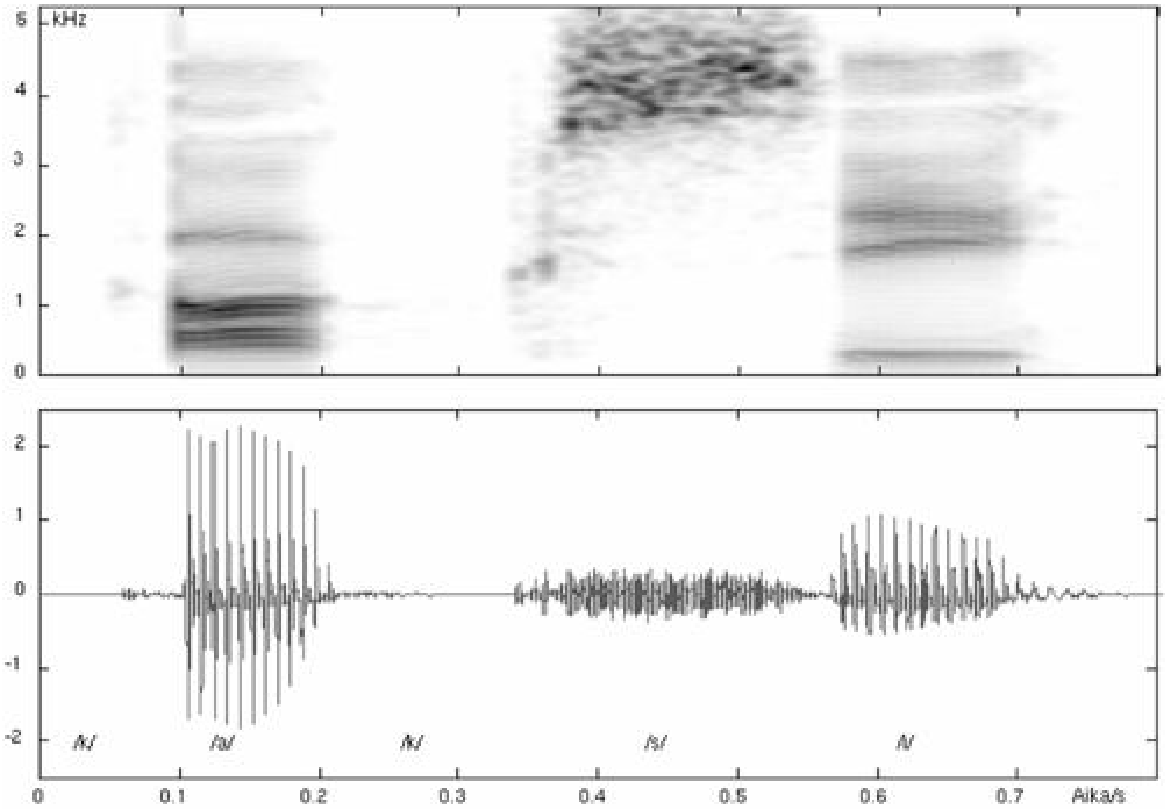
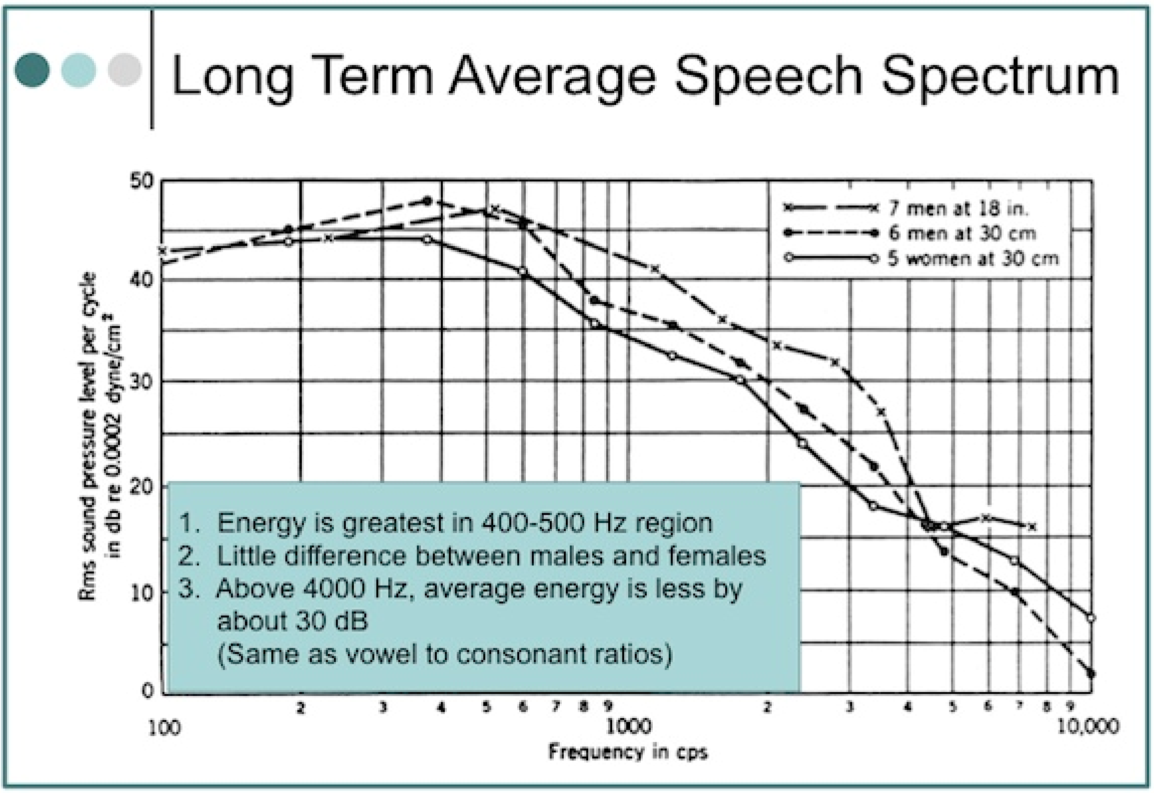


Figure 1: Spectrogram and time- domain waveform of the Finnish word ’’kaksi’’(two). The x-axes represent the time and the y-axes are the frequency (upper graph) and the signal amplitude (lower graph). Figure obtained from [3].



Long Term Average Speech Spectrum

1. Energy is greatest in 400-500 Hz region
2. Little difference between males and females
3. Above 4000 Hz, average energy is less by about 30 dB
   (Same as vowel to consonant ratios)

Figure 2: The long-time average distribution of speech energy over the range of audible frequencies. Measurements were performed in 7 men at 18 in (≈46 cm), in 6 men at 30 cm and 5 women at 30 cm. Figure obtained from [34] using data for the upper curve from [4].

Masking types

The first observations for the masking phenomenon were done by Mayer in 1876 while listening to an organ. Mayer believed that low-frequency sounds are better maskers than high-frequency sounds but because of lack of proper equipment, no experiments were performed [7]. Later, when proper and convenient equipment was developed a more experimental research was performed with the first experimental data obtained from Wegel and Lane in 1924 [8]. In this first controlled experiment about masking, Wegel and Lane used as maskers six different sinusoidal signals at different frequencies and another sinusoid signal was used as the test tone at various frequencies above and below the masker tone. The purpose was to determine the test signal's threshold shift for different masker's levels. When the masker and the signal were close in frequency, and since the two tones under study were present at the same time, beats occurred. In order for this problem to be avoided, not entirely successful though, in later experiments, narrow band noise was used.

Masking patterns

The masking patterns (or sometimes called masking audiograms) are graphs that present the masked threshold as a function of the frequency of the test signal. Fig. 3 shows an example of the masked audiogram obtained from Egan and Hake experiments in 1950 [9].

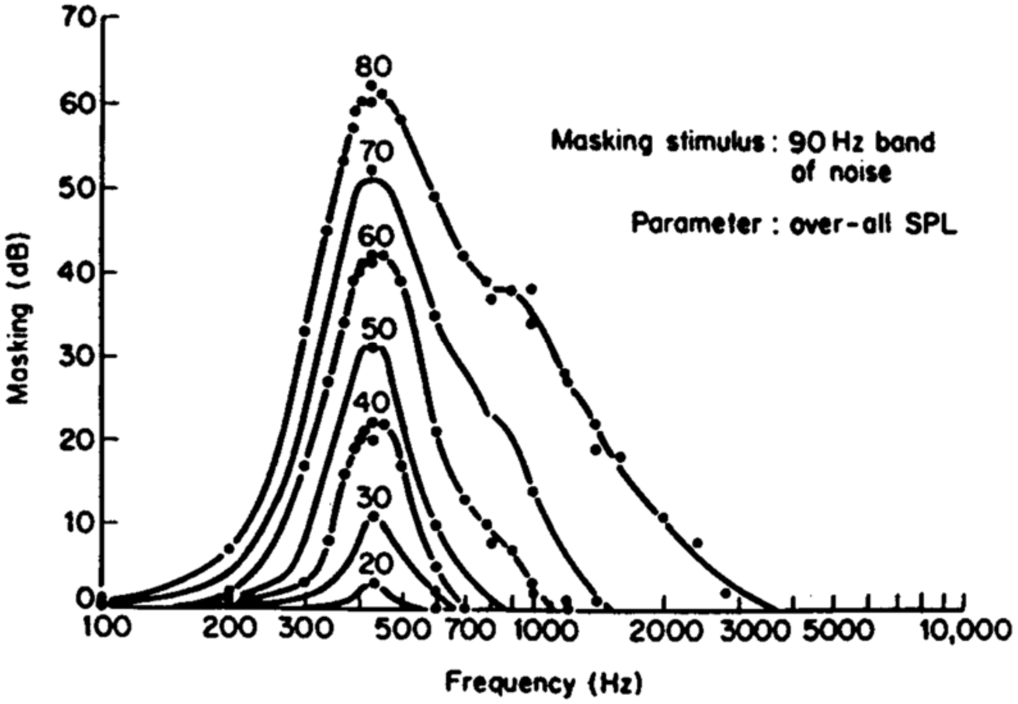


Figure 3: Masking patterns for narrow-band noise (90 Hz wide, 410 Hz centered) presented at various over-all SPL (dB ref $2x10^{-5}$ Pa). The shift in the threshold of the test signal is presented as a function of the signal's frequency. Figure obtained from [9].

In Fig. 3, one can see that as the level of the masker is increased the less symmetrical the curves become. The slope on the right side (towards high-frequencies) is less steep and is highly dependent on the level of the masker while on the other hand the slope towards low-frequencies seems to be independent of level, that means that if the level of a low-frequency masker is increased by 10 dB (as the step used at the experiment) the threshold at high-frequencies is elevated more than at low-frequencies. This pattern is known as upward spread masking.

Critical bandwidth and spectral masking

The cochlea is a coiled structure located in the inner ear and the around 20.000 haircells in the cochlea detect, and to a certain degree, amplify temporal and frequency pattern of sound waves and convert them into neural signals. The low frequencies are detected by sensory cells at the inner tip of the cochlea (apex) [33]. In Fig. 4, the vibration pattern on the basilar membrane, at different frequencies is presented.

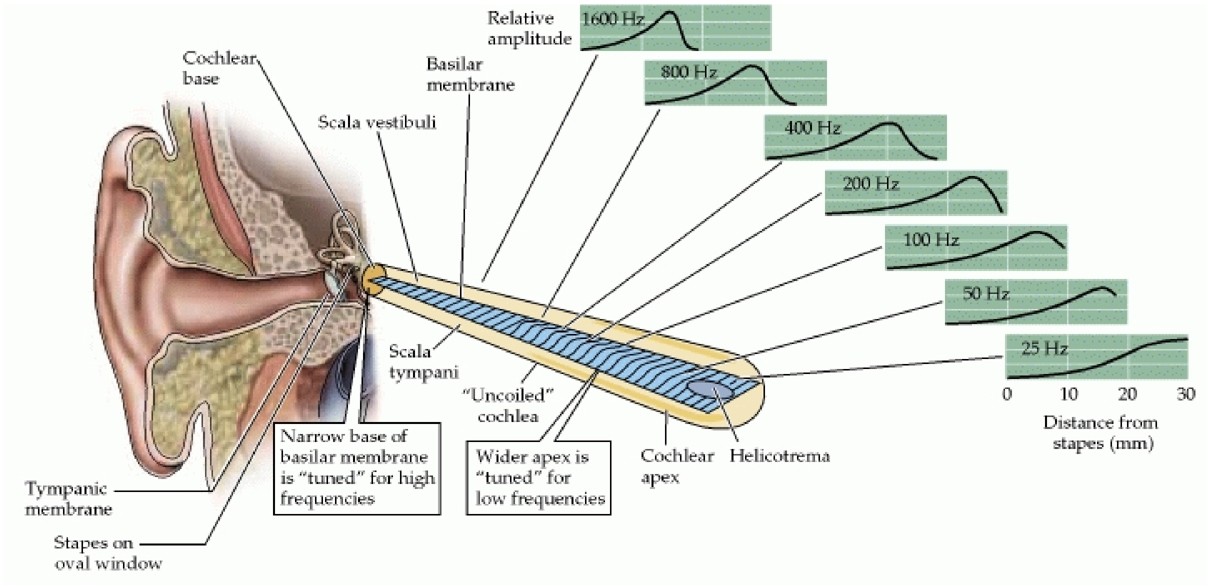


Figure 4: Schematic map of frequency representation on the basilar membrane. Maximum amplitudes of the traveling waves along basilar membrane at different frequencies. Cochlea has been uncoiled for clarity. Figure obtained from [33].

Inside the cochlea, auditory filters are created to help the listener detect signals in noisy environments. Each time, the filter used is the one with center frequency close to the one of the signal and allows the signal to pass while removes many components of the noise. The amount of the noise that actually passes through the filter has a masking effect on the signal when both, the signal and the noise, have the same power. The threshold of the signal is increased or decreased according to the signal to noise ratio at the output of the auditory filter. The more the noise bandwidth increases the more noise passes through the filter, as long as the noise bandwidth is smaller than the one of the filter. When the noise bandwidth exceeds the filter bandwidth, there is a point that further increase of the noise bandwidth does not alter the threshold of the signal (and the noise passing through the filter). The bandwidth at which this phenomenon happens is called the critical bandwidth. The concept of the critical bandwidth, introduced by Fletcher, assumes that the part of a noise that effectively masks a tone is the part of the noise spectrum centered around the frequency of the tone [10].

Temporal masking

The auditory masking is known as frequency or spectral masking when it occurs in the frequency domain, as mentioned, and temporal masking when it occurs in the time domain.

Speech is a sound with strong temporal structure that varies in energy and frequency. As compared to simultaneous masking, which occurs when two sounds overlap in time, temporal masking occurs when the masker stimuli is presented before (pre-masking) or after (post-masking) the test sound and it is also called non-simultaneous masking. In Fig. 5, an illustrative example of the three different temporal regions of masking is presented.

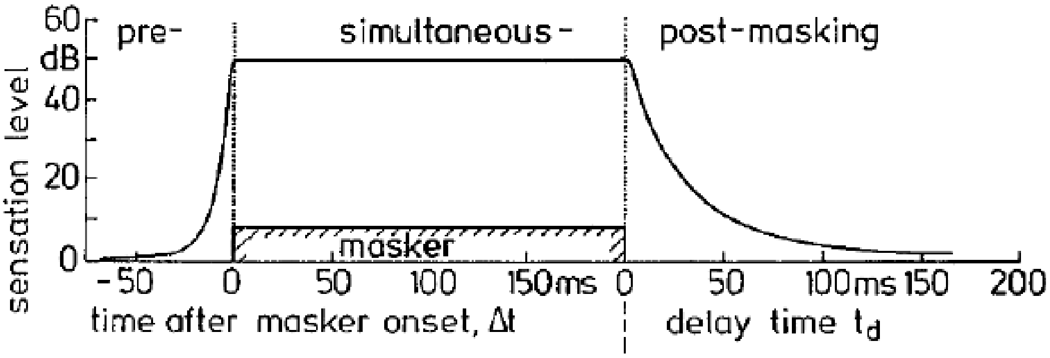


Figure 5: Illustration of the three different temporal regions of auditory masking. Figure obtained from [10].

As one can see in Fig. 5, Δt is the time that is related to the presence of the masker while t_d starts when the masker has stopped (also called delay time).

The pre-masking occurs before the masking stimuli. The phenomenon is poorly understood despite the number of studies that have been published. It depends on whether the subjects are trained or not and it is not clear whether it depends on the duration of the masker or not [11]. The pre-masking alone plays a secondary role. It can last about 20 ms in any condition and represents an effect that takes place just before the masker sound appears. Imaging a build-up time situation then we might have a good explanation of pre-masking. Assuming a quick build-up time for a very loud masker or a slower for a not loud masker then the pre-masking phenomenon might be more understandable. Because of the very small duration, the effect is usually ignored [10].

Right after the pre-masking effect, the simultaneous effect occurs within the Δt time scale. The two sounds are present at the same time making the effect depending on the duration of the masker sound, as it is shown in Fig. 5. When the simultaneous masking phenomenon occurs the shift of the test signal's threshold follows the masking patterns that were analyzed in 3.3.1. The simultaneous masking is highly dependent on the duration of the masker, the frequency analysis of the two signals and their relative intensity [11].

After the masker sound is switched off the post-masking effect occurs. Even though the masking stimuli are not present during the delay time scale, the masking effect is still produced in the auditory nerve as a change in detectability of the test stimulus, like a decay effect in the human hearing system. The third region of temporal masking can last more than 100 ms and ends after about 200 ms delay. It is a dominant effect and it is strongly depending on the duration of the masker (nonlinear effect) [10].

Fig. 6 presents an example of the combined effects of spectral and temporal masking.

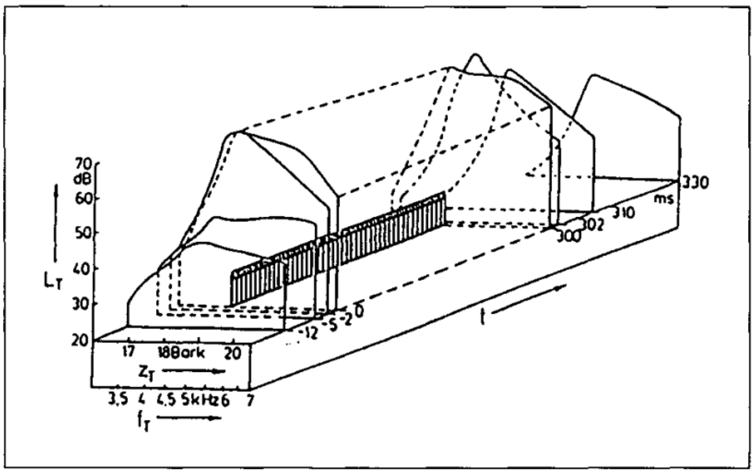


Figure 6: The masking pattern of a 4 kHz impulse (300 ms duration) as a function of time and frequency. Figure obtained from [12].

In Fig. 6, the level of a just audible impulse sound is plotted as a function of the frequency and the temporal relation to the masker which is presented with the block of arrows between 0 and 300 msec. The spectral masking patterns follows the patterns that were analyzed in paragraph 3.3.2, while with regards to the temporal effect, the post-masking effect is obvious after the 300 msec. The negative values of the time represent the pre-masking effect in the neural processing of the sounds [12].

Low-frequency noise masking patterns

As shown in Fig. 4, low frequencies are detected by sensory cells at the inner tip of the cochlea hence vibrate the full length of the basilar membrane which could be a reason for the low frequency masking pattern.

Most of the older studies were concentrated on frequencies above 500 Hz (usually around 1 kHz) and later it became clear that additional data on low-frequency masking effects had to be included. In 1976, Tobias performed systematic experiments in order to investigate further the low-frequency masking patterns [13].

In Tobias experiment 11 college-age normal hearing men were used as subjects. Before and after the actual test, a Bekesy threshold measurement (using a narrow band noise stimulus) and a series of discrete, pure-tone thresholds at the frequencies under study were performed in order to record each subject's personal thresholds and to use these data as a basis. Five different masking tones were used at 150, 250, 350, 500 and 1000 Hz, for three different levels. All frequencies were tested at 40, 60 and 80 dB Sensation Level (SL) except the 150 Hz tone which was tested at 30, 50 and 70 dB SL because of a limitation in the equipment's available output.

In Fig. 7, 8, 9, 10 and 11 the masking audiograms for each frequency separately are presented.

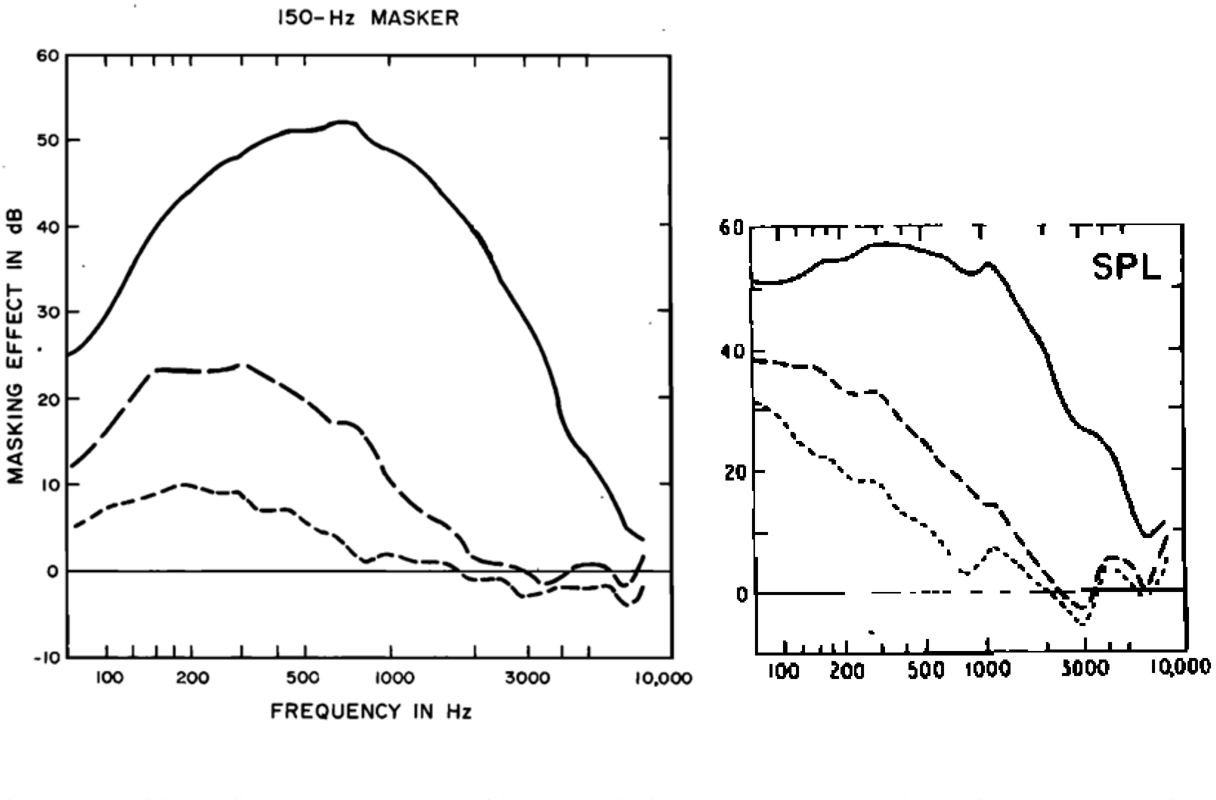


Figure 7: Masking audiogram for 150 Hz masking tone. The lower curve represents the masker at 30 dB SL, the middle curve at 50 dB SL and the upper curve at 70 dB SL. The curves represent mean values of all subjects. The figure on the right shows the data plotted on SPL ordinate. Figures obtained from [13].

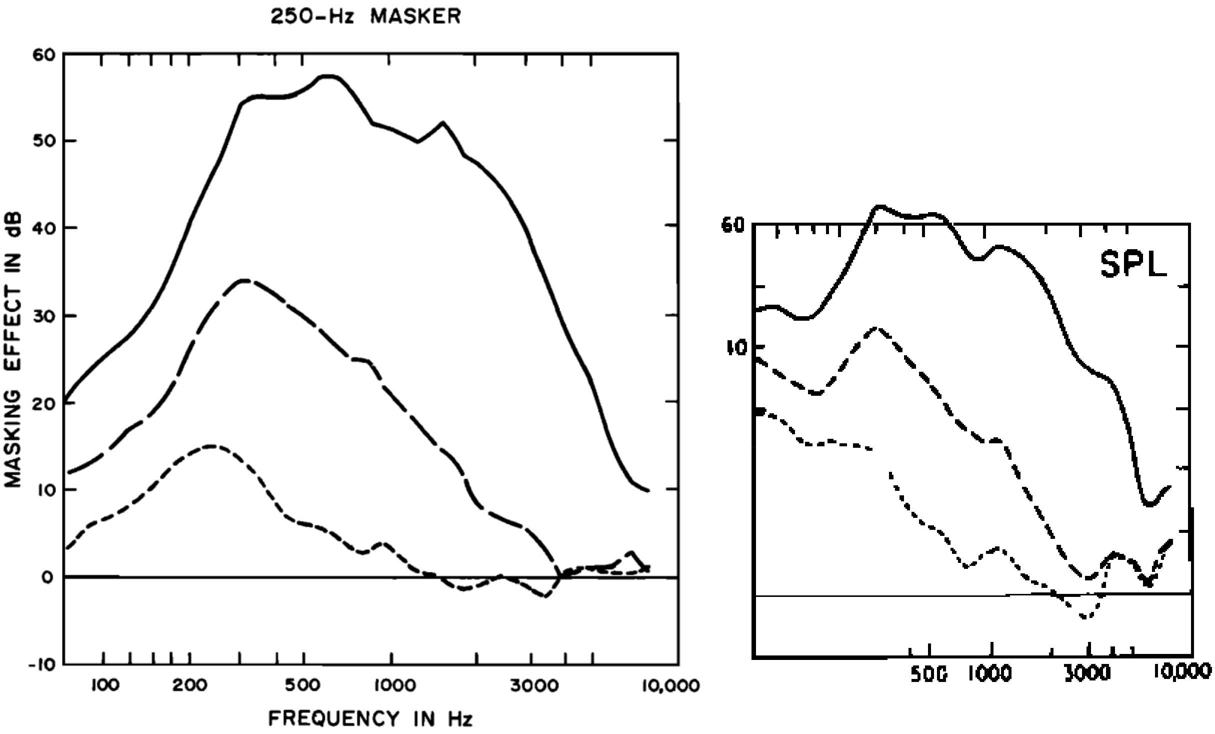


Figure 8: Masking audiogram for 250 Hz masking tone. The lower curve represents the masker at 40 dB SL, the middle curve at 60 dB SL and the upper curve at 80 dB SL. The curves represent mean values of all subjects. The figure on the right shows the data plotted on SPL ordinate. Figures obtained from [13].

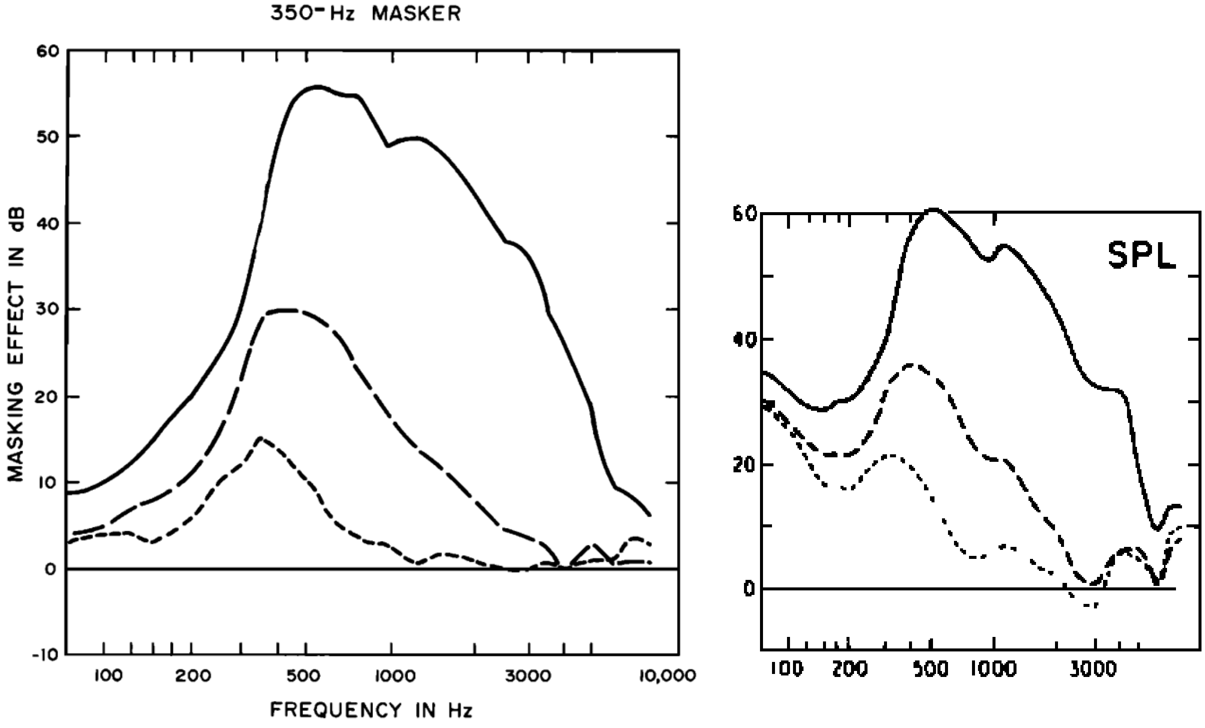


Figure 9: Masking audiogram for 350 Hz masking tone. The lower curve represents the masker at 40 dB SL, the middle curve at 60 dB SL and the upper curve at 80 dB SL. The curves represent mean values of all subjects. The figure on the right shows the data plotted on SPL ordinate. Figures obtained from [13].

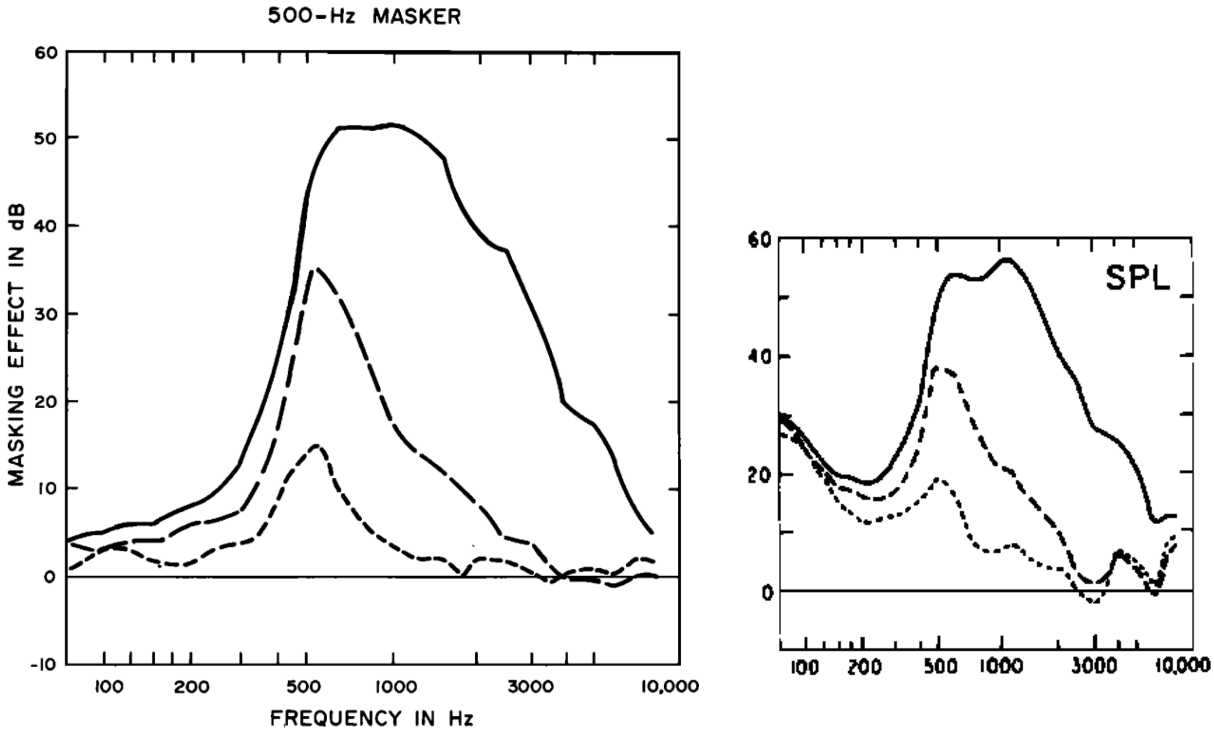


Figure 10: Masking audiogram for 500 Hz masking tone. The lower curve represents the masker at 40 dB SL, the middle curve at 60 dB SL and the upper curve at 80 dB SL. The curves represent mean values of all subjects. The figure on the right shows the data plotted on SPL ordinate. Figures obtained from [13].

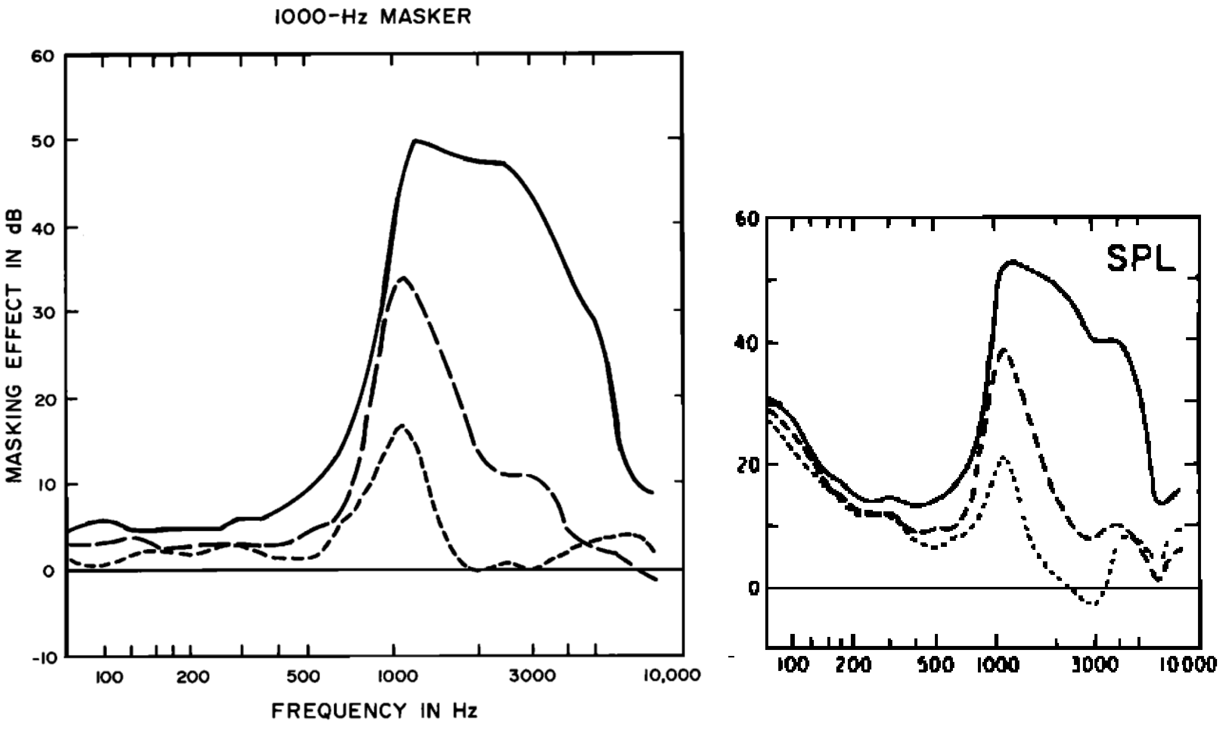


Figure 11: Masking audiogram for 1000 Hz masking tone. The lower curve represents the masker at 40 dB SL, the middle curve at 60 dB SL and the upper curve at 80 dB SL. The curves represent mean values of all subjects. The figure on the right shows the data plotted on SPL ordinate. Figures obtained from [13].

The results from Tobias experiment show that the maximum masking effect, which is showed with the large peak in Fig. 7, 8, 9, 10 and 11, occurs around (and slightly above) the frequency of the masking tone for the lowest tested level of each frequency. As the level increases then a shift towards higher frequencies at the maximum masking effect (peak) occurs. The frequency shift is more obvious for the three lower frequencies and the higher level of the 500 Hz, while is not obvious for the higher masking frequency (1 kHz).

In Fig. 12, the curves for the higher tested levels and for all frequencies are presented in order to have a more illustrative comparison.

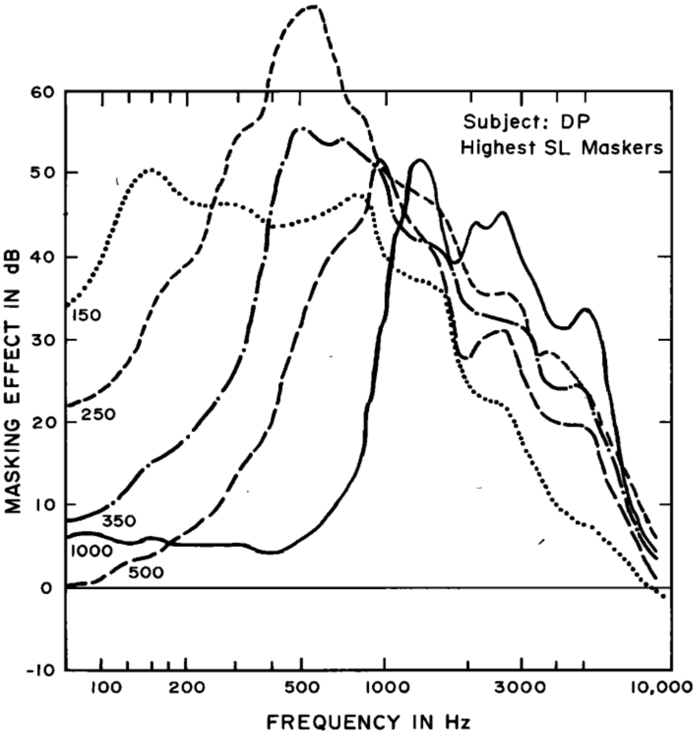


Figure 12: Masking audiogram for all masking frequencies, at the higher tested level, for one subject. The 150 Hz tone was at 70 dB SL and the others at 80 dB SL. Figure obtained from [13].

One can clearly see in Fig. 12 that the masking patterns for the lower frequencies (at the highest tested levels) are not similar to those at middle and high frequencies. While the maximum masking effect for 1 kHz happens slightly above this frequency, for the lower frequencies the shift towards the higher frequencies is greater and the masking effect is broader affecting a larger range of frequencies.

It should be noted that the levels of the masker sounds are presented in dB SL (Sensation Level), which indicates the level in relation to the pure tone threshold of each test subject. For example, the masker sound presented at 40 dB SL at 500 Hz is 40 dB higher than the individuals' hearing threshold at the same frequency. Furthermore, the figures showing the obtained data in SPL were plotted by the author based on the individuals' audiograms and the measured data.

Tobias also tried to test for effects on the data from procedural biases. The data from the bias-correction tests were the same to the initial results. Also using a low-frequency narrow-band noise as a masker and a pure tone as the test signal, obtained data were indistinguishable from the initial data obtained.

A general conclusion from Tobias experiment would be that low-frequency tones have similar masking patterns, highly dependent on the level of the masker that shifts the maximum masking effect towards higher frequencies.

Masking of speech

Effect on speech intelligibility

The masking of speech depends on the signal–to–noise ratio over the range of frequencies involved in speech [4]. The signal-to-noise ratio is simply the signal level (speech in this case) minus the noise level in dB. A negative value of this ratio means that the level of the noise is higher than the test signal. In Fig. 13 the intelligibility of different types of speech test materials in the presence of noise are presented. Data were obtained by Miller et al. in 1951 [17], after performing a series of articulation tests. Syllables, words and sentences were read by talkers and listeners were asked to try to identify them. The signal-to-noise ratio was altered by keeping the average voice level constant and changing the level of the noise.

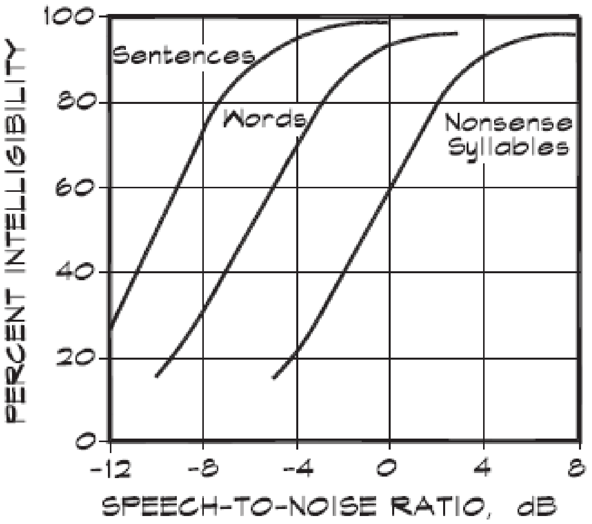


Figure 13: Intelligibility of three different types of speech test materials in the presence of noise. Figure obtained from [18].

It is clear in Fig. 13 that even if the signal-to-noise ratio is negative, the sentences and words are still intelligible. Also the type of speech material influences the outcome of the test. For example, in order to achieve a 60% of speech intelligibility (SI) the values of SNR for sentences, words and nonsense words are -10 dB, -5 dB and 0 dB respectively. Miller indicates that the SI is also affected by the way the stimuli are presented to the listener. For example, in Fig 13, for SNR=-8 dB the intelligibility of the words is much lower than the intelligibility of sentences which is probably due to the influence of redundance, e.g. ‘’apples grow on…….‘’ that makes understanding of sentences easier than isolated words [17]. Also, the scores can be affected if the speech stimuli are presented from a talker live or recorded or with visual presentation [19]. One of the strongest influences, though, is related to the individual characteristics. Scores vary according to the experience of the listener (general experience or familiarity to people, with hearing disability and to talker’s accent), the age (on average, younger listeners give higher scores than older listeners, but this could also be due to the fact that older people are more likely to experience hearing loss) [19, 20]. The interaction of these variables is complex and a subject of investigation.

Low frequency noise effect on speech intelligibility

Pickett in 1959 [21], performed an experiment in order to test the speech intelligibility in a low-frequency masking noise. The noise was set at three different levels, 85, 105 and 115 dB. The speech was unfiltered and low-frequency energy to the masking noise was consecutively added by a set of filters with high-pass cutoff frequencies of 600, 300, 150, 75 and 20 Hz. Three trained male talkers read 25 words to four listeners for the given combination of the experiment. The results together with the unfiltered noise are presented in Fig. 14.

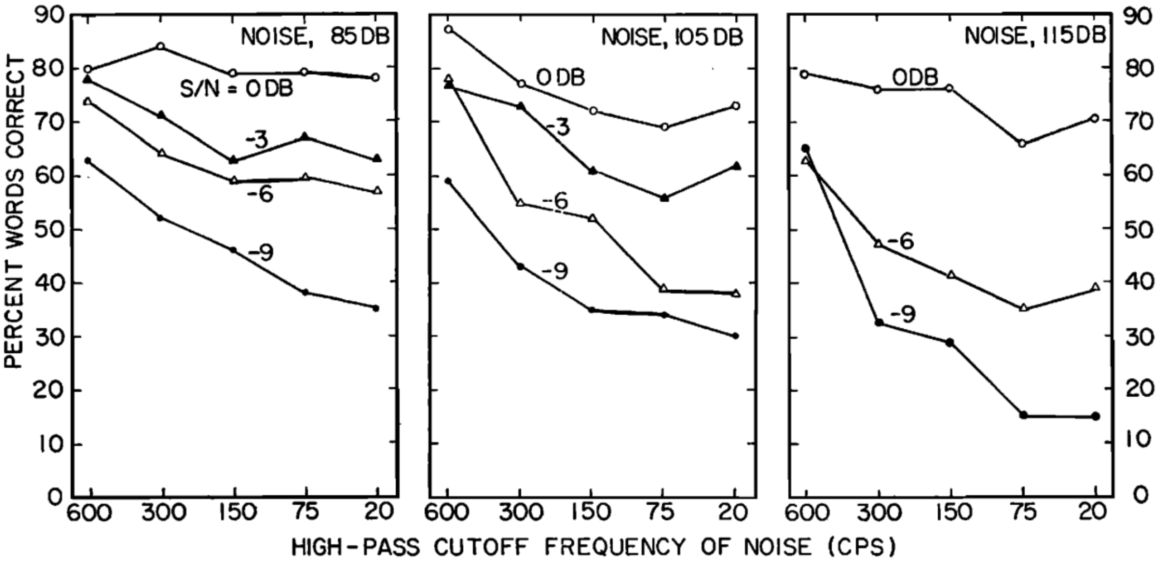


Figure 14: The effect of low-frequency noise on speech intelligibility. The y-axis shows the percentage of the words were heard correctly and x-axis the noise frequency in Hz. The curves show the SNR measured with a Volume Unit on unfiltered speech and unfiltered noise increasing the low-frequency energy in the noise from 600 to 20 Hz (left to right). Each block shows the different overall noise level (85, 105 and 115 dB). Figure obtained from [21].

In Fig. 14 one can see that the speech intelligibility decreases as the noise is filtered from 600 to 75 Hz. Furthermore, the masking effect of Low-frequency noise decreased with decreasing S/N ratio [21].

The importance of Room Acoustics on speech intelligibility

Effect of reverberation and noise in speech recognition

Room acoustics play a significant part on the transmission of speech and speech intelligibility. Among the most important factors that affect the speech intelligibility are the acoustical properties of the enclosure in which the speech is transmitted between the talker and the listener, the distance, the early and late reverberation and the background noise. High levels of background noise can mask important information of the speech signal.

When a sound is generated in a room by a source, e.g. the talker, the receiver (listener) receives the direct sound followed by the early and late reflections which are summed up and form the reverberant field. The reverberation time depends on the size and the characteristics of the room. In Fig. 15, the idealized room response to an impulse excitation is presented.

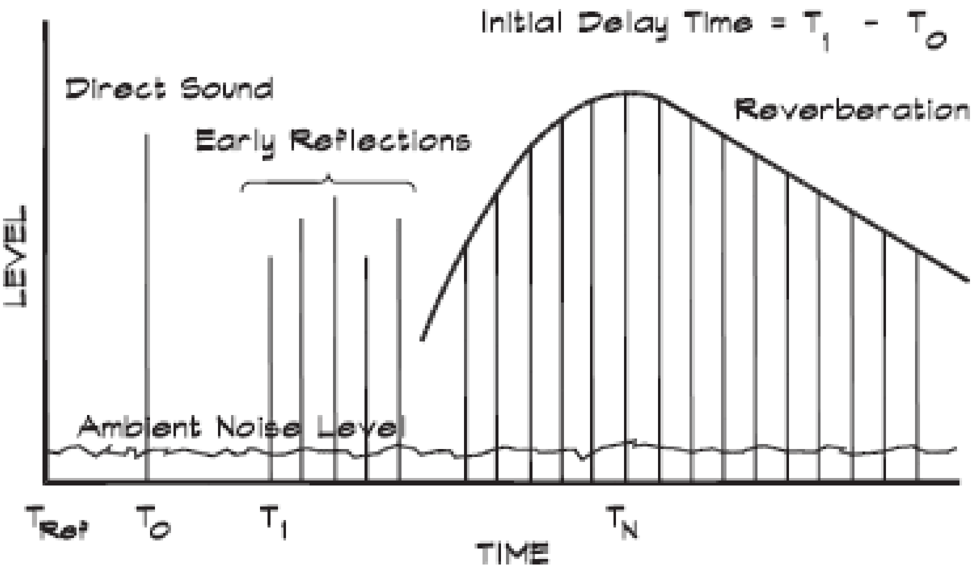


Figure 15: The idealized room response to an impulse excitation. Figure obtained from [18].

At T_0, in Fig. 15, the direct sound is presented with the first reflections, known as early reflections, to follow at T_1. The initial delay time, which is the T_1 - T_0, should be between 20-50 msec (preferable for speech) and the early reflections can increase the speech intelligibility and audibility in noisy environments [22]. The late components of reverberation arrive at $T_N > 50$ msec and can decrease speech intelligibility. The decreased speech intelligibility increases as T_N is longer and/or also in the presence of background noise [18].

As mentioned, speech intelligibility depends on the signal–to–noise ratio (SNR) over the range of frequencies involved in speech (Fig. 13). The study of Boothroyd [23], outlines the effects of the reverberation and the acoustic properties of the room on the perception of speech. In Fig. 16, the predicted long-term average speech level as a function of distance from the source in a classroom is presented.

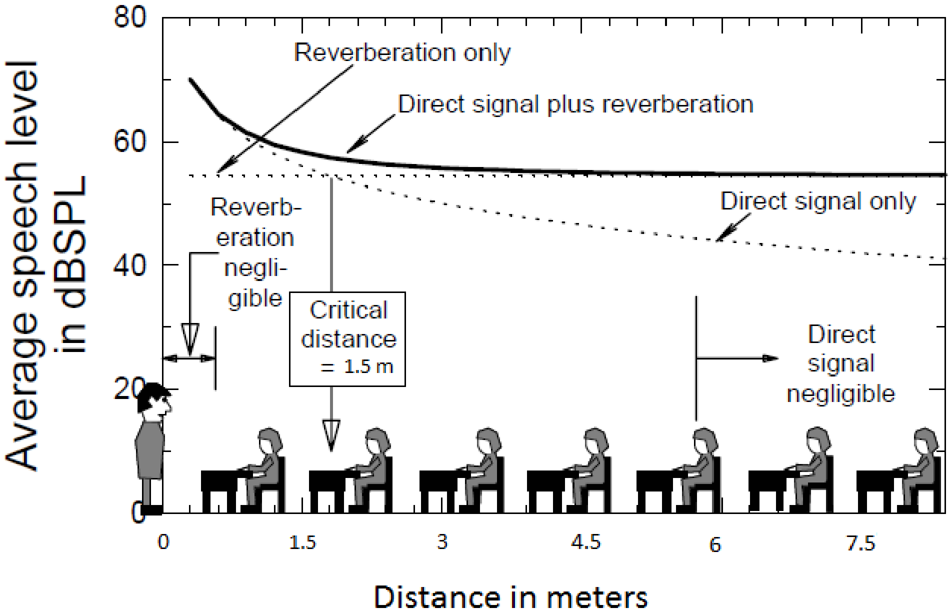


Figure 16: Predicted long-term average speech level a function of distance from the source in a classroom (9X6X3 m) with RT=0.5 sec. Figure obtained from [23].

Listeners located far away from the speaker (students in last three rows), receive the reverberant speech while most of the other students receive a mixture of the direct and the reverberant speech. The student located at a distance of 6 m or greater, receive the direct sound by 10 dB, or more, weaker than the reverberant sound and the received signal can be considered entirely reverberant (direct signal negligible). The acoustical energy of the speech that travels from the speaker to the listeners is spread over the large area of the classroom and decreases in dB. To a first approximation, the effect follows the 6 dB rule that suggests that, in free field, the level of the direct sound is decreasing by 6 dB for every doubling of the distance.

In Fig. 17, the spectrogram of a short phrase with and without reverberation is presented.

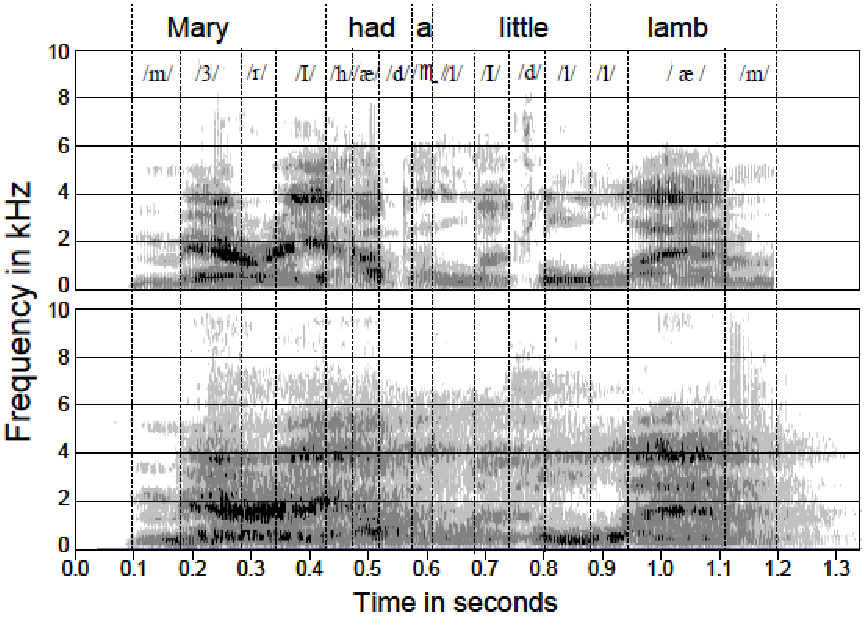


Figure 17: Spectrogram of the short phrase ''Mary had a little lamb'' without reverberation (upper plot) and with reverberation (RT=0.5sec) (lower plot). Figure obtained from [23].

Boothroyd [23], with this spectrogram illustrates the sound components and how they intrude to the next ones. The upper plot shows the phrase without any reverberation while in the lower plot a RT of 0.5 sec was added. With the spectrogram in Fig. 17, the equivalence of the late reflections to the noise is illustrated and also how the speech can basically mask itself. The late components of reverberation interfere with intelligibility and the speech signal generates its own masking noise.

Previous research [35] support the importance of minimizing the noise and reverberation in classrooms and report age related changes in speech recognition in noisy and reverberant environments for elementary school-aged children.

Speech recognition of 48 normal hearing children (7 to 14 years) and 12 normal hearing young adults (23 to 30 years, served as control participants) was measured in three virtual listening environments. Also, a virtual class was designed to reflect a model of an occupied rectangular classroom (9.3x7.7x2.8m) with average RT of 0.4 for frequencies between 125 and 4000 Hz. The three virtual environments were RT= 0 sec (pseudo-anechoic PA) in order to mimic clinical testing conditions, RT = 0.4 sec at 2 m (R2m) distance from the speaker, in order to represent students sitting in the first row of a small classroom and RT = 0.4 at 6 m (R6m) distance from the speaker, in order to simulate students sitting in the last row, close to the wall.

The sentence stimuli were presented at 65 dB SPL via headphones and the noise levels varied from 55 to 75 dB SPL creating different SNR. The test subjects were asked to repeat the sentences encouraged to repeat as much as they could hear and/or guess to fill the gaps. The test was repeated for randomized order of the virtual environments and the different SNR. The study found a negative effect of reverberation and noise in speech recognition with an overall improvement in performance with increasing age. The group of the youngest children (who tend to be in the noisiest classrooms) was the one more affected by the combination of noise and reverberation.

Effect of sound absorption on speech recognition

It is known that in order to alter the acoustic environment in a room with regards to RT, absorption can be added. A study conducted by Pekkarinen et al. [24], investigates the effect of a sound absorbing treatment on the speech discrimination. A classroom (volume 9.5x6.5x3.5 m) and a multipurpose hall (volume 36x17x7 m) were used for the speech tests. In the experiment, 152 normal hearing pupils served as test subjects in the classroom and 193 normal hearing pupils in the multipurpose hall. The speech discrimination was tested by sentences, isolated di- and trisyllabic words and nonsense words read by a male in an anechoic chamber. All the speech tests were played to the students before and after the acoustic treatment through loudspeaker in quiet and at two noise levels. Before the experiments, the pupils were familiarized with the speech test by listening to them one time. In the classroom, the pupils were sitting at their desks at a distance of 2 m from the loudspeaker and in the multipurpose hall they were sitting in rows facing the loudspeaker with the first row at a distance of 3 m from the source.

The classroom was acoustically treated with mineral wool panels (50 mm thick) which covered most of the back wall and part of the ceiling. The speech level was set at 75 dBA because of the high natural background noise. In the multipurpose hall, mineral wool was embedded in board-construction and covered the walls of the room but not the ceiling due to ventilation system. The speech level was set at 60 dBA.

The experiment was conducted with background noise in order to simulate the everyday listening conditions of the students, which was generated by a sound source (B&K 4224) with noise spectrum as shown in Fig. 18.

The noise source was placed close to the loudspeaker and the S/N of +2 and +7 dB were used in the classroom and 0, +5 and +10 dB in the multipurpose hall, based on pilot study.

Fig. 19 and 20 show the improved reverberation time in both rooms.

The reduction of RT in the classroom was almost the same for the whole frequency range with a mean reduction of 1 s while in the multipurpose hall the reduction of RT is much higher and quite flat at lower frequencies between 250 and 500 Hz.

The combined effect of RT and noise for both rooms is presented in Fig. 21.

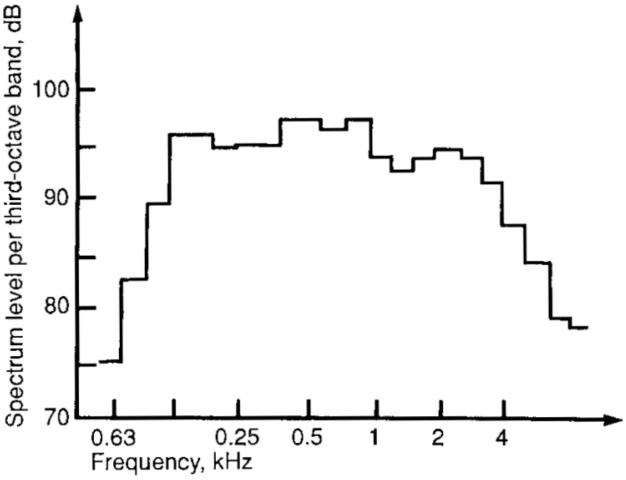


Figure 18: Spectrum of noise in third- octaves produced by B&K 4224 (Ref. 1 pW). Figure obtained from [24].

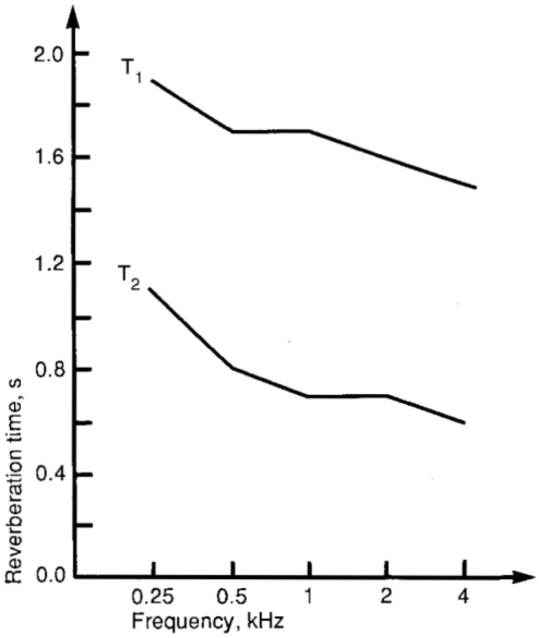


Figure 19: Reverberation time as a function of frequency in the classroom before (T_1) and after (T_2) the acoustic treatment. Figure obtained from [24].

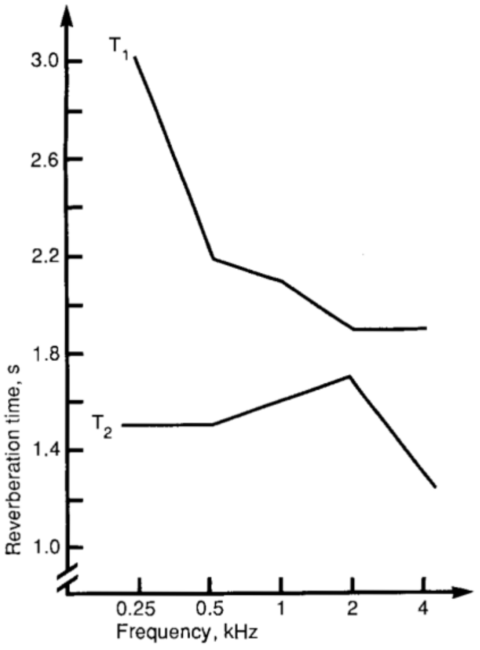


Figure 20: Reverberation time as a function of frequency in the multipurpose hall before (T_1) and after (T_2) the acoustic treatment. Figures obtained from [24].

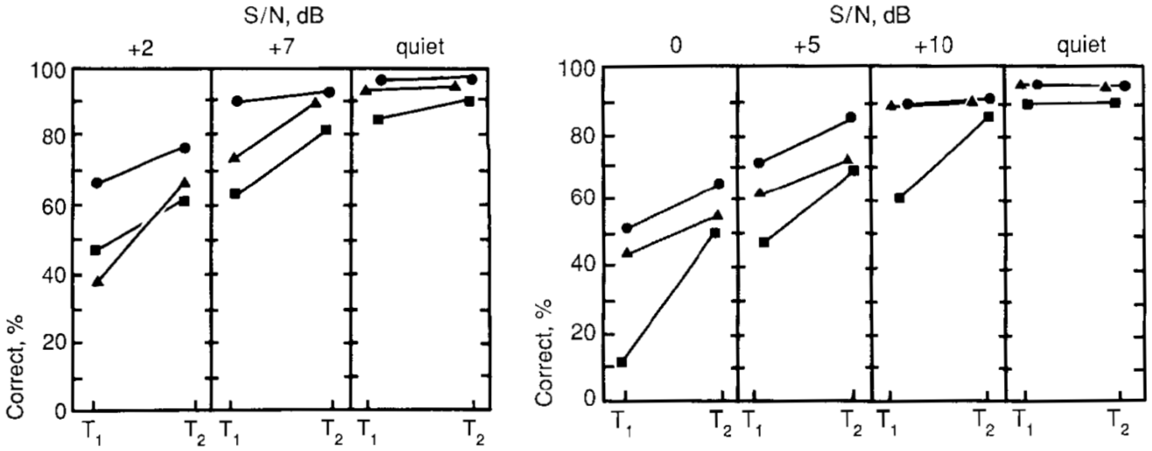
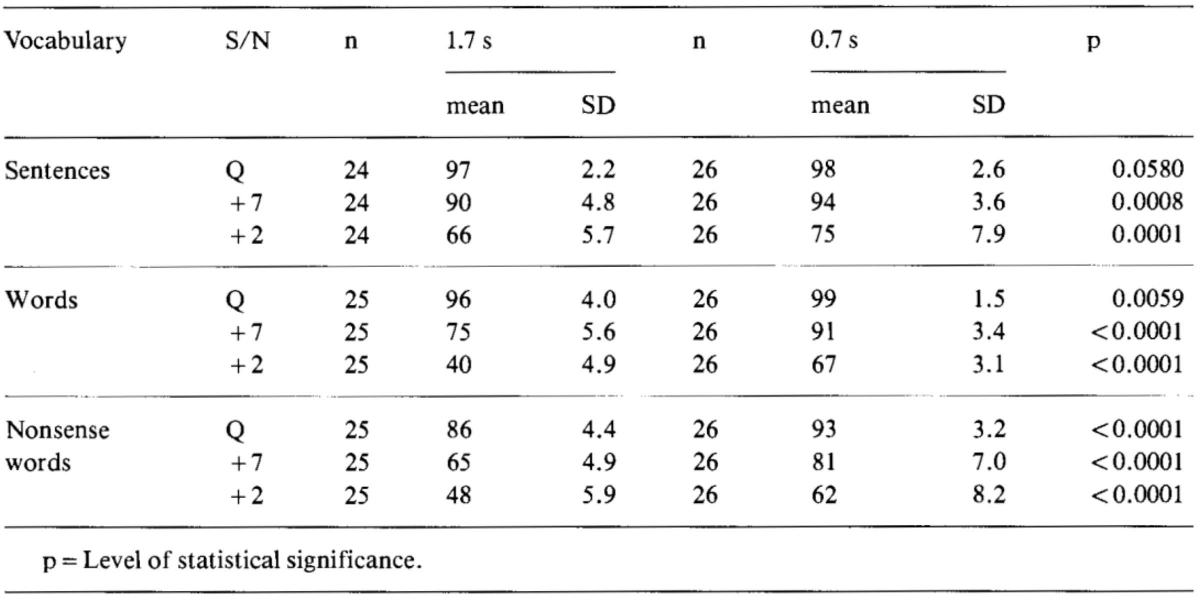


Figure 21: Left figure, speech tests discrimination at different noise levels (different S/N in quiet, +2, +7) before (T_1) and after (T_2) the acoustic treatment of the classroom. (●= sentences, ▲= words, ■= nonsense words). Right figure speech tests discrimination at different noise levels (different S/N in quiet, 0, +5, +10) before (T_1) and after (T_2) the acoustic treatment of the multipurpose room (●= sentences, ▲= words, ■= nonsense words). Figures obtained from [24].

Improving the RT of both rooms (make it shorter) gives a combined effect on the discrimination of the three different speech tests. In the classroom the discrimination of all stimuli decreased when noise added with higher levels of decrease for the longest RT, before the treatment (T_1). In each case, though, there is a high improvement in speech discrimination after the acoustic treatment (T_2) especially for the nonsense word. Similar results were obtained also for the multipurpose room with the improved RT giving higher percentages of perceived speech stimuli. It is noticeable though that even for the high RT (before the treatment) the percentages of the words and sentences intelligibility are high enough and especially for the case were SNR = +10 dB are the same for T_1 and T_2. For both cases, a t test was performed and the levels of statistical significance were obtained. For especially the cases of words and nonsense words the interaction of RT and noise was highly significant.

Table 2 and 3 present the results for the classroom and the multipurpose room respectively, before and after the acoustical treatment.

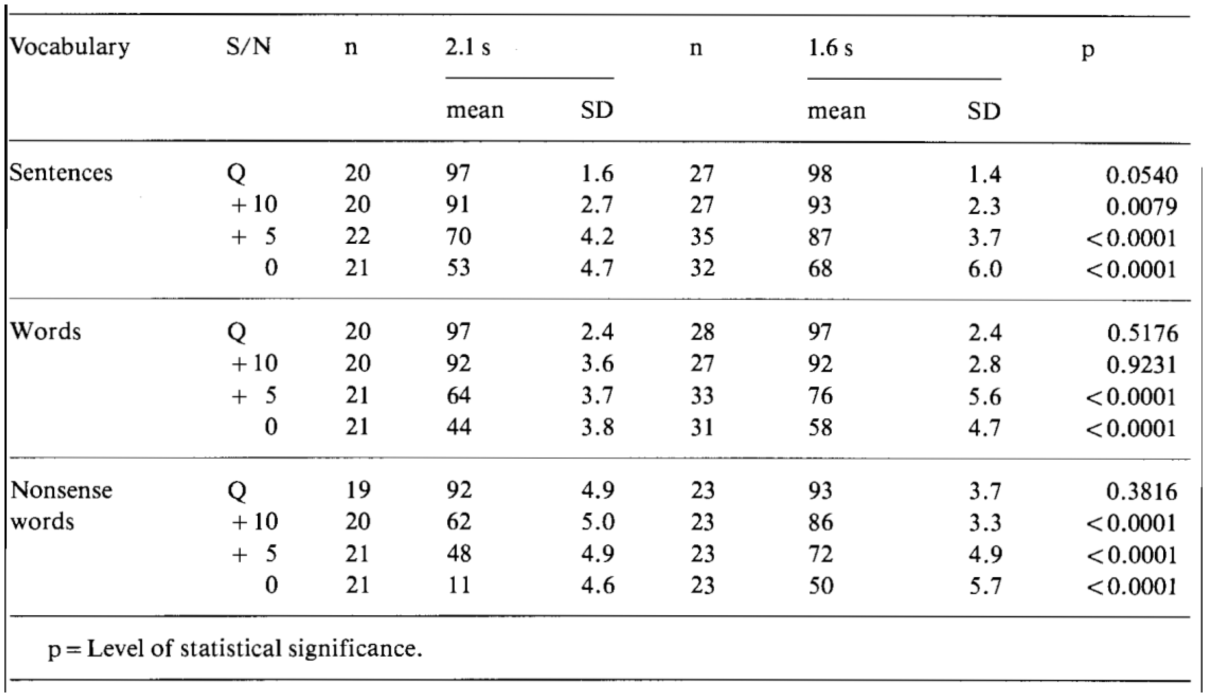
Table 2: Speech discrimination percentages in quiet (Q) and in noise (SNR) before (T=1.7 sec) and after (T=0.7 sec) the acoustical treatment of the classroom. Table obtained from [24].



Vocabulary	S/N	n	1.7 s		n	0.7 s		p
			mean	SD		mean	SD	
Sentences	Q	24	97	2.2	26	98	2.6	0.0580
	+7	24	90	4.8	26	94	3.6	0.0008
	+2	24	66	5.7	26	75	7.9	0.0001
Words	Q	25	96	4.0	26	99	1.5	0.0059
	+7	25	75	5.6	26	91	3.4	<0.0001
	+2	25	40	4.9	26	67	3.1	<0.0001
Nonsense words	Q	25	86	4.4	26	93	3.2	<0.0001
	+7	25	65	4.9	26	81	7.0	<0.0001
	+2	25	48	5.9	26	62	8.2	<0.0001

p = Level of statistical significance.

Table 3: Speech discrimination percentages in quiet (Q) and in noise (SNR) before (T=2.1 sec) and after (T=1.6 sec) the acoustical treatment of the multipurpose room. Table obtained from [24].



Vocabulary	S/N	n	2.1 s		n	1.6 s		p
			mean	SD		mean	SD	
Sentences	Q	20	97	1.6	27	98	1.4	0.0540
	+10	20	91	2.7	27	93	2.3	0.0079
	+ 5	22	70	4.2	35	87	3.7	<0.0001
	0	21	53	4.7	32	68	6.0	<0.0001
Words	Q	20	97	2.4	28	97	2.4	0.5176
	+10	20	92	3.6	27	92	2.8	0.9231
	+ 5	21	64	3.7	33	76	5.6	<0.0001
	0	21	44	3.8	31	58	4.7	<0.0001
Nonsense words	Q	19	92	4.9	23	93	3.7	0.3816
	+10	20	62	5.0	23	86	3.3	<0.0001
	+ 5	21	48	4.9	23	72	4.9	<0.0001
	0	21	11	4.6	23	50	5.7	<0.0001

p = Level of statistical significance.

From Table 2, one can see that in quiet there are no significant changes in the classroom after the treatment. Keeping the noise stable (SNR = +7 dB) the discrimination of the words and nonsense words was improved by 16 percentage units with the shorter RT of 0.7 s and a small improvement (4 percentage units) for the sentences. Greater differences were obtained for SNR=+2 especially for words and nonsense words with an improvement of 27 percentage units and 14 percentage units respectively for the two revereration times.

From Table 3, the same results were obtained for the multipurpose room in quiet with no significant differences in the stimuli discrimination. For SNR=+10 dB the scores for sentences and words are almost the same for the two RT but for the nonsense words an improvement of 24% in understanding was obtained. High differences in the discrimination of all test stimuli were obtained by increasing the noise (SNR=+5 dB) and decreasing the RT with higher scores in the nonsense words (24%). Finally, high differences were also observed with SNR = 0 dB, with the sentences, the words and nonsense words discrimination to improved by 15%, 14% and 39% respectively.

To summarize, the reduction of RT and the noise levels improved the speech intelligibility especially for the nonsense words which was the most difficult case while intelligibility was easier for sentences. Speech intelligibility was improved for both the classroom and the multipurpose rooms and a comparison between the rooms are difficult to make as the original reverberation and the resulting reverberation are not comparable. For the multipurpose room the greater reduction of RT was achieved at the low frequencies (from 3.0 sec to 1.5 sec at 250 Hz and quite flat up to 500 Hz). This great reduction could contribute to the great improvement on intelligibility in the low signal to noise ratios. For the classroom the reverberation was attenuated quite evenly across frequencies and also this scenario resulted in a great improvement in speech intelligibility, for the low signal to noise ratios.

Acoustic comfort in rooms

Obtaining high acoustic comfort and sound quality in communication rooms (e.g. offices, conference rooms, classrooms, restaurants etc.) is often of secondary importance during the design and the planning of a new project. Literature and research on the effect of the low-frequency noise are scarce and usually the low frequencies are neglected.

The research and development institute Fraunhofer IBP in Germany, applied and tested a compound panel absorber (CPA) in many multipurpose rooms. This low-frequency absorber was applied first in offices and multipurpose rooms and visitors and untrained users noticed a positive effect on speech articulation and understanding. Fuchs et al. conducted a small study [25] using the low-frequency absorber in different communication rooms and measured the RT before and after the acoustic treatment and also questioned the users and visitors to express their opinion. The study aimed to inform acousticians and sound professionals and not for scientific purposes.

The use of low-frequency absorber was based on the idea of damping the low-frequency modes of the room and keep a rather flat, at low-frequencies, RT. When designing small rooms with communication mission, damping the modes at low frequencies increases the acoustic comfort in the room. For example, a small room of volume 7x5x3 m = 105 m^3 for frequencies between 0 and 100 Hz has 22 modes (from Eq. 1).

$$N = \frac{4}{3}\frac{\pi V}{c^3}f^3 + \frac{\pi S}{4c^2}f^2 + \frac{L}{8c}f \tag{1}$$

Where N is the number of modes, V, S and L are the volume, the surface and the length of the edges of the room and c is the speed of sound. Example and Eq. were obtained from [26].

The low-frequency modes in small rooms are well separated (first mode for this room is at 24 Hz) and the transmission of the signal is irregular between each modal frequency with the resonance effect to elevate the sound pressure [26]. In simple words, the low-frequency components are amplified in undamped rooms and the response of the room at low-frequencies can cause an unwanted effect on speech intelligibility.

Fuchs et al. [25] used a low-frequency absorber, as mentioned, in different communication rooms in order to improve the acoustical comfort. In Fig. 22 the RT before and after the acoustic treatment in a small conference room is presented.

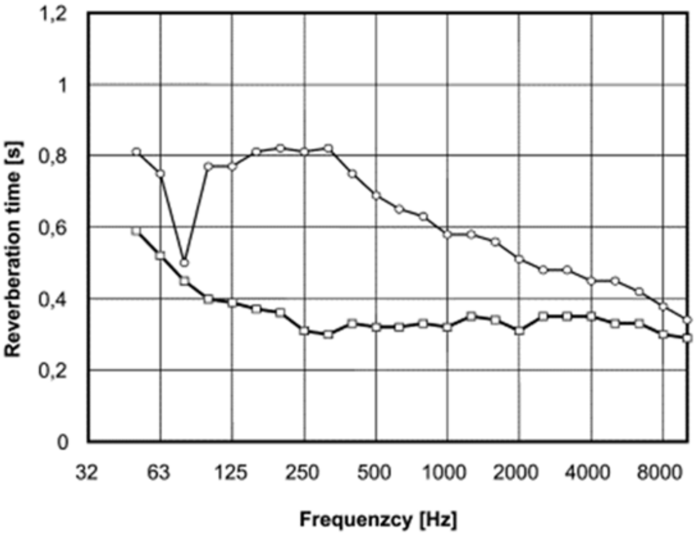


Figure 22: Reverberation Time as a function of frequency in a conference room before (upper line) and after (lower line) the acoustic treatment. Figure obtained from [25].

The conference room with dimensions 5.4x5.3x2.9 m with a concrete ceiling and plasterboard walls with heavy claddings and carpet on the floor showed a reasonable low frequency RT, before the acoustic treatment that does not exceed 0.8 sec. The higher RT values are below 500 Hz. An acoustician could probably think that there is no need of improvement of the room. But even if the room seems acoustically ‘’dry’’ in higher frequencies (also at frequencies that carry the useful information of human speech), it would resonate at its eigenfrequencies (below 250 Hz). The use of the low-frequency absorber gave a rather flat reverberation time with somewhat higher value at 63 Hz. Since the study was aiming to inform acousticians about the absorber, no listening tests were conducted but the users and visitors found the sound quality of the room significantly improved for both speech and video conference.

Speech intelligibility for normal hearing and hearing impaired people

The combined effect of noise and RT on communication and speech intelligibility affects normal or impaired hearing people but for different signal-to-noise ratio and RT. People using hearing aids have an improved speech audibility in quiet but not in noisy and reverberant environments [27].

A common complaint among listeners with sensorineural hearing loss (SNHL) is a difficulty to understand speech in noisy listening environments. Individuals with SNHL have reduced frequency selectivity and temporal resolution which makes it more difficult to perceive rapidly changing or temporally close sounds [28]. This may increases the influence of upward and temporal masking (pre-masking, post-masking).

For normal hearing adults, speech perception is not significantly affected until the level of the background noise is the same as the speech level (SNR = 0 dB) while SNHL listeners require SNR to be improved by 4-12 dB and even by additional 3-6 dB in rooms with moderate levels of reverberation, in order to achieve similar scores of speech perception as the normal hearing listeners. Furthermore, speech perception for normal hearing listeners is not compromised until the levels of RT exceed approximately 1 sec while for SNHL listeners RT should be even shorter and not exceed 0.4 sec [29]. According to the American Speech-Language-Hearing Association [31], the requirements in order to achieve a comfortable acoustical environment for listeners with SNHL are a SNR=+15 dB, with RT=0.4-0.6 seconds. The background noise levels in an empty room should not exceed 30-35 dBA [29].

Finitzo et al. [30], investigated the speech perception abilities for children with SNHL using mososyllabus words and varying the SNR (quiet, +12, +6, 0) and the RT (0, 0.4, 1.2 s).

Table 4: Mean speech recognition in percentages of correct answers by children (8-12 years old) with normal hearing and with SNHL for monosyllabic words for different SNR and RT. the test subjects were 12 children of each group. Table obtained from [29] based on the study [30].

	Groups	
Testing condition	**Normal hearing (%)**	**Hearing impaired (%)**
RT = 0.0 second		
Quiet	94.5	83.0
+ 12 dB	89.2	70,0
+ 6 dB	79.7	59.5
0 dB	60.2	39.0
RT = 0.4 seconds		
Quiet	92.5	74.0
+ 12 dB	82.8	60.2
+ 6 dB	71.3	52.2
0 dB	47.7	27.8
RT = 1.2 Seconds		
Quiet	76.5	45.0
+ 12 dB	68.8	41.2
+ 6 dB	54.2	27.0
0 dB	29.7	11.2

In Table 4, one can see that the normal hearing children had a better performance for all combinations of RT and SNR. It is noticeable also, that in cases of very good scores for normal hearing children, for example for SNR=+12 dB and RT=0.4 s, which it is a case that indicates a very good classroom environment, the children with SNHL obtained low percentage scores.

A listening test was performed by Nilsson and Hammer [38] in Skenehomsskolan, Billesholm in order to evaluate the speech intelligibility for normal hearing listeners and listeners with simulated minimal degrees of hearing loss. Different types of absorbers were applied in a classroom and listening tests were performed in order to classify the different treatments with respect to speech intelligibility.

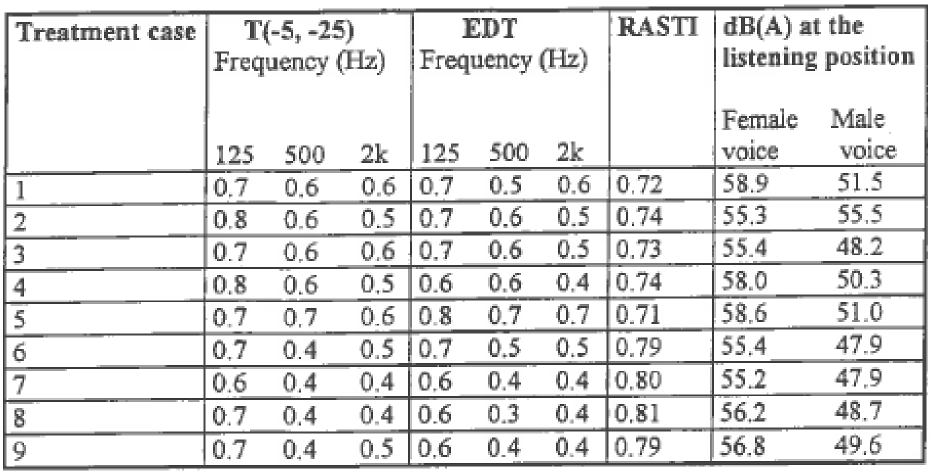
Two groups of listeners were used as test subjects. One group was consisted of normal hearing individuals (25 listeners) and the other of listeners with special earplugs attached to their ears in order to simulate a minimal degree of hearing loss (23 listeners). The earplugs gave a rather constant damping of 15 to 30 dB (rel. the threshold of hearing) at frequencies between 125 Hz and 8 kHz. This type of hearing loss can be compared to a secondary effect of a cold or ear inflammation and is usually of a temporary nature.

Male and female speech (anechoic recorded) were reproduced by a loudspeaker that was located at the teacher’s desk. Dummy-head recordings were made for 13 different absorber treatments of the classroom (9 were selected for the listening test). A small monitor loudspeaker was used as a sound source. The listening position was the lower part of the classroom. The volume of the class room was

11.7x7.2x3 m. Table 5, shows the measured data for each treatment case. Both groups of listeners were asked to choose the preferable acoustic environment with regards to speech intelligibility.

With respect to the speech intelligibility, cases 6, 7, and 8 were the most preferable before 1, 2, 3, 4 and 5 (see Fig. 23). The cases that were rated as the most preferable, show slightly higher RASTI values towards lower RT (especially at 500 Hz). Furthermore, slightly shorter EDT values were measured when the reverberation time was reduced from 0.7 sec to 0.6 sec (case 7). The RT is short enough to meet the suggested guidelines of [31]. Lowering the RT to 0.6 seconds at 125 Hz seem to have improved subjectively perceived speech intelligibility.

Table 5: Measured data on room acoustic parameters.



Treatment case	T(-5, -25) Frequency (Hz)			EDT Frequency (Hz)			RASTI	dB(A) at the listening position	
	125	500	2k	125	500	2k		Female voice	Male voice
1	0.7	0.6	0.6	0.7	0.5	0.6	0.72	58.9	51.5
2	0.8	0.6	0.5	0.7	0.6	0.5	0.74	55.3	55.5
3	0.7	0.6	0.6	0.7	0.6	0.5	0.73	55.4	48.2
4	0.8	0.6	0.5	0.6	0.6	0.4	0.74	58.0	50.3
5	0.7	0.7	0.6	0.8	0.7	0.7	0.71	58.6	51.0
6	0.7	0.4	0.5	0.7	0.5	0.5	0.79	55.4	47.9
7	0.6	0.4	0.4	0.6	0.4	0.4	0.80	55.2	47.9
8	0.7	0.4	0.4	0.6	0.3	0.4	0.81	56.2	48.7
9	0.7	0.4	0.5	0.6	0.4	0.4	0.79	56.8	49.6

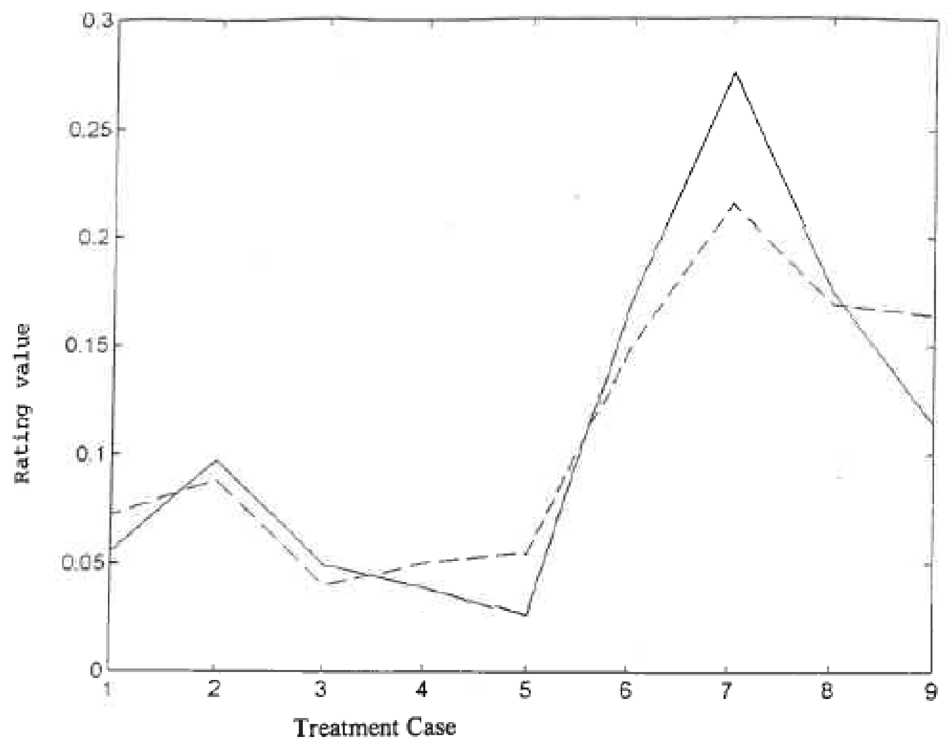


Figure 23: Comparison of the preferences for the subjects with (dashed line) and without (solid line) earplugs. Both female and male voices are included. The x-axis shows the different treatment cases (from 1 to 9).

Another study that aims to test and address the effect of the changes in acoustics on teachers and pupils with normal and impaired hearing, is the ‘’Essex Study’’ [32]. Four similar in size classrooms in the Math department of Sweyne Park School were used for the study. All the classrooms had hard walls and ceiling and windows on two sides. Three of them were treated acoustically in order to comply with the public standards for acoustic comfort in the classroom. The fourth was remained untreated and used as control room. More than 400 students (including 17 hearing impaired students) and 10 teachers were involved in the study.

The reverberation times were measured in all of the rooms for all different cases and also before the acoustical treatment. Also, the sound pressure levels were measured in the classroom during lessons in order to determine whether there was a significant difference as a function with RT. Teachers and students completed questionnaires about the acoustic comfort in the classrooms.

From the questionnaires and the interviews, the overall impression from staff and students was that the working environment was improved for all the people involved in the study. The acoustic environment in the rooms was perceived ‘’quieter’’ and ‘’calmer’’ while teachers with more or less experience found the changes a big improvement which could be also due to the change in the behavior of students, including hearing impaired students, and teachers when using a treated room.

Finally, a group of 25 acousticians was invited to evaluate the treated rooms and express their experience. After a short presentation, some time spent in the rooms, they completed the semantic differential questionnaires. The cases with the shorter RT in lower frequencies were rated as the best for listening and speaking. The case with the higher RT was rated more negative.

The general outcome of the study showed a very strong correlation between RT and sound quality in the classrooms. Also strong correlation was found between the measured sound levels and the teachers’ report for very significant improvements in behavior in the rooms with the lower RT.

Conclusions

The purpose of this review was to improve our knowledge on whether low frequency noise affects speech intelligibility and whether reducing low frequency noise would improve conditions for communication. The scientific background for this topic is scarce, with many of the theoretical studies being carried out more than 40 years ago. However some interesting conclusions can be drawn and are outlined below.

Several studies show that noise more efficiently mask higher frequencies (upward masking) than lower frequencies (downward masking). The upward spread of masking is strongly dependent on the level and the frequency of the masker, so a low frequency noise at a moderate to high level is an efficient masker of higher frequencies. Low frequency noise can hence theoretically be an efficient masker of speech and may reduce speech intelligibility. Studies of low frequency masking patterns are though rare but one older study indicated that sounds of frequencies up to about 350 Hz may be efficient masker of speech at sound pressure levels normally occurring at offices or education premises. The masking effect of low frequencies is also supported by one other study where increasing low frequencies in the noise reduced the percentage of words correctly heard.

The vowels have their main energy in the low and mid frequency range of the speech spectrum, while consonants have their energy in the mid and high frequeny range. The comparatively higher amplitude of the vowels further contribute to the risk of masking the sounds of consonants, especially in a reverberant environment and for groups that are more vulnerable in non optimal listening conditions such as hearing impaired people, children, elderly and non native listeners.

Most of the studies reviewed and presented in this report, investigate the effects of Reverberation Time together with the Signal to Noise Ratio on Speech Intelligibility and acoustic comfort. Some of the studies reviewed and presented were not related to specific studies of low frequency noise, but should be seen as outcomes strengthening the importance of a good acoustic environment for speech intelligibility. A good acoustic environment has been documented to be specifically important for vulnerable groups such as young and old, non native listeners and people with hearing impairments.

Future work

The results of this review point to several important directions for future work. Some of these directions are presented below:

Overall, more research is needed on how to obtain the optimum room acoustics and to avoid masking of speech in general and for vulnerable groups.

Specifically there is a need to:

- Better investigate the low frequency masking patterns, reproducing older studies using modern techniques.
- Previous studies on the effect of low-frequency absorbers in different communication rooms, based their conclusions on Reverberation Time/Room Acoustic measurements and questions to the users. However the results are derived from small studies, with poor methodology and need to be extended and validated. Listening tests should also be advocated.
- Very important findings were documented on the combined effect of different reverberant environments and signal to noise ratios. Similar investigation on hearing impaired children and young adults could help the deployment of a more comfortable acoustic environment for educational settings and preschools.
- It is known that the human brain has the ability to select the useful information and fill in the gaps between the intelligible words. The effect of low frequency background noise for this ability should be evaluated.
- Methodology studies evaluating the interaction of the different variables like age, experience of listener, cultural and language differences, type of speech material, in relation to a variety of room acoustic measures needs further research in order to achieve a better general understanding of low frequency effects on Speech Intelligibility

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The first report was published in 2010.

Published by the Unit for Occupational & Environmental Medicine
Gothenburg, 2017-08-24
ISBN 978-91-86863-13-5

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Site: www.amm.se and gupea.ub.gu.se/handle/2077/34412