Masking behaviour of tonal and noise maskers for noise targets

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There is no effect in nature
without a reason;
understand the reason
and you do not need experiment.

Leonardo da Vinci
(1452-1519)

Contents

Introduction

To facilitate the understanding of the experiments described in this report, a short introduction is given about the auditory system. In addition an overview is given about masking and modeling of the auditory system and digital coding of acoustic signals.

Structure and functions of the auditory system

Peripheral system

The peripheral auditory system (the ears) can be divided into three parts, namely the outer, middle and inner ear. The outer ear consists of the pinna (the visible part of the ear) and the meatus (the ear canal). The pinna helps in sound localization while the meatus transfers the sound to the tympanic membrane. Together with the tympanic cavity, the ossicles and the Eustachian tube does the tympanic membrane form the middle ear. The function of the middle ear is to transmit the sound energy from the air in the ear canal to the fluids inside the cochlea. The inner ear consists of the cochlea, the vestibule and the semicircular canals. The vestibule and the semicircular canals contain balance organs, while the cochlea transforms pressure variations into neural impulses. For a cross-section of the ear, see Fig. 1.

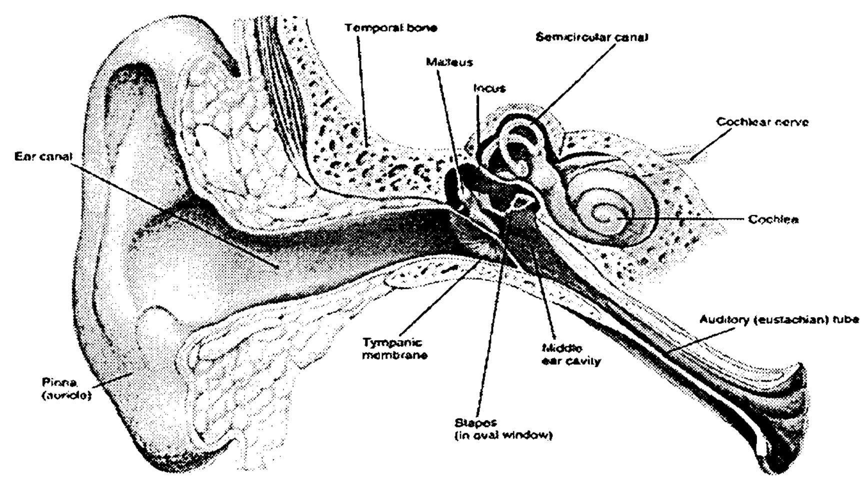

Fig. 1: Illustration of the peripheral part of the auditory system, showing the outer, middle and inner ear (Visible Productions, http://visiblep.com).

The cochlea can be described as a coneshaped spiral, that is divided into three chambers: the scala media, scala vestibuli and scala tympani. The middle chamber is called the scala media and it is separated from the scala vestibuli by Reissner's membrane and from the scala tympani by the basilar membrane. At the base of this spiral the pressure variations caused by the stapes enter the scala vestibuli and they move towards the apex. Because the fluids inside the cochlea are incompressible the pressure variations move Reissner's membrane as well as the basilar membrane. The pressure variations can then be equalized via the fluids in the scala tympani and the movement of the round window. The hair cells in the organ of Corti (which can be found on the basilar membrane in the scala media) transduce the movement of the basilar membrane into electrochemical activity which is transmitted to the auditory nerve.

In short: the acoustic stimulus travels first via the pinna through the meatus. After that its energy is transmitted by the tympanic membrane, through the tympanic cavity to the malleus (hammer), incus (anvil) and stapes (stirrup). Then the stapes activates the oval window and the energy passes through the vestibule and the cochlea to the auditory nerve.

Central system

The auditory nerve terminates in the cochlear nucleus. Then the auditory pathway continues from the cochlear nucleus via the superior olivary nucleus to the inferior colliculus, then to the medial geniculate nucleus and it ends in the auditory cortex. The auditory cortex is essential for complex auditory tasks like sound localization and speech perception. This central system of the auditory system can be found in the brain.

An effect that a sound has on auditory neurons is that a number of them are activated. The neuron that is most sensitive to the center frequency of the sound will be excited most, other neurons less. The total number of excited neurons does increase with increasing sound level, in this way the energy of a narrow band stimulus is spread over a number of neurons, and this pattern is called the excitation pattern of the stimulus.

Masking

In an everyday situation a lot of sounds reach the ear at the same time. For instance when two people are having a conversation, it is possible that they have to adjust their level of speech to background noise like a playing radio. If the person talking is hardly audible anymore because of this background noise then the speech is called to be masked by the background sound. Masking is defined as the raising of the threshold of audibility of a sound due to the presence of another sound.

An example of classical data on masking comes from Egan and Hake (1950) (for the results of one subject, see Fig. 2). In this case two sounds are presented simultaneously over headphones to a subject. One of these sounds is called the target (or the signal) and the other one is called the masker. The masker is presented with a fixed level and the level of the target is variable. During an experiment the level of the target is adjusted towards the lowest level at which it can be heard by the subject and this level is called the masked threshold (or the signal level). In Fig. 2, this value is plotted on the y-axis of the graphs. On the x-axis the variable frequency of the sinusoidal target can be found. The masker in this experiment was a sinusoid of 400 Hz (circles) or a 90-Hz-wide noise (squares) with a center frequency of 410 Hz. Both maskers had an overall level of 80, 60 or 40 dB SPL.

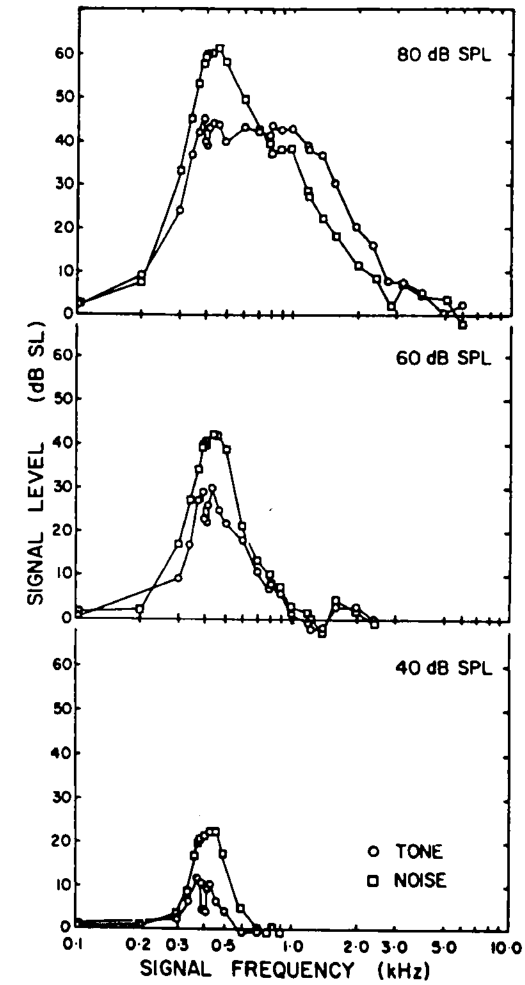

Fig. 2: Masking patterns of a tonal target (or signal) with variable center frequency for two types of maskers: a sinusoid of 400 Hz (circles) or a 90-Hz-wide noiseband (squares) with a center frequency of 410 Hz. The masker had a total level of 80, 60 or 40 dB SPL. This is a replotted version of data of Egan and Hake (1950) by Johnson-Davies (1981).

The results in Fig. 2 show that for an on-frequency situation (when target and masker have the same center frequency) the noise masker masks more than the sinusoid, because the thresholds are higher for the noise. Also the curve of masked threshold versus frequency and the influence of the masker level is different for a noise versus a sinusoidal masker. This so-called masking pattern has steeper slopes and a higher on-frequency threshold for a noise masker compared to a tonal masker. With an increase in level, the high-frequency side of the masking pattern becomes less steep, while the slopes for the low-frequency side increase somewhat in steepness. Both types of masker show this effect, but the change with level is stronger for the tonal masker than for the noise masker. This results in a linear growth of masking for an on-frequency situation, a less-than-linear growth for the low-frequency side of the excitation and masking pattern and a more-than-linear growth for the high-frequency side.

According to Fletcher (1940) the peripheral auditory system behaves like a bank of bandpass filters. Every point on the basilar membrane only responds to a certain range of frequencies and thus behaves as a bandpass filter. So all these points together would then form a bank of overlapping bandpass filters in which the auditory filters are all sensitive to different center frequencies. This theory is generally accepted.
It is usually assumed that a masked threshold corresponds to a certain signal-to-noise ratio at the filter output (Patterson and Moore, 1986). For instance Fletcher (1940) measured masked thresholds for a tonal target and a noise masker that increased in bandwidth. He found out that with increasing bandwidth the target was masked more. So more noise intensity passed through the auditory filter and the signal level had to increase to keep the signal-to-noise ratio constant. Beyond a certain bandwidth the masked thresholds remained constant. Fletcher called the noise bandwidth at which the masked thresholds stopped to increase the critical bandwidth.

A term that needs an explanation in order to get a better understandig of the rest of this report is distortion product. Sometimes when two sounds are presented at the same time one or even two lower tones can also be heard. These tones are a consequence of the nonlinear behaviour of the basilar membrane and are called distortion products or combination tones. The perceptually most relevant distortion product is the Cubic Distortion Tone (CDT). For two primary components of frequencies f1 and f2 (with $f1<f2$) the CDT has a frequency of $2f1-f2$.

Modeling and digital coding

A lot of research is done, and will be done in the future, to derive a good representative model of the auditory system (e.g. Patterson et al., 1995, Verhey and Dau, 1995, Dau et al. 1996a, b). The reason is to make it possible to predict the perception of sounds when for instance somebody listens to music. The research necessary to get a better understanding of the perception of sound is done by means of psychoacoustics, and in particular in the field of masking (the term masking is described above). The information resulting from these psychoacoustical experiments can also be used to improve the quality of musical recordings, to improve transmission and to decrease the space needed on a digital storage device, such as a Compact Disc (CD) or a Digital Compact Cassette (DCC), for the same piece of music, without quality loss.
A piece of music that is stored on for instance a CD or a DCC is first sampled and than this sample is coded in bits (the original analog signal is changed into a digital signal). For a high quality signal more bits are used and/or more samples are taken. Researchers try to decrease the number of bits necessary to code a sound and still keep the quality optimal, because in this way sounds can be stored more efficiently (Brandenburg and Stoll, 1994). The number of samples can only be decreased to a minimum of about twice the maximum audible frequency (about 20 kHz). So the only possibility is to reduce the number of bits per sample, but this number determines the maximum and minimum level of the signal that can be realized. The lower the bits per sample ratio, the more quantization noise is generated and for a low input level the signal is no longer audible due to this quantization noise. So another approach was necessary and one of these was found in subband coding, which is the division of the audible frequency range into smaller subbands. In each of these bands the number of bits can be

changed depending on the information present in the signal. This can reduce the number of bits used per sample for instance from 16 to 4 or even less. To learn more about the possibilities of subband coding psychoacoustical masking experiments were done (Veldhuis and Kohlrausch, 1995). Also the experiments described in this report are done for this purpose and that is why a bandwidth of 750 Hz is used for targets, because this is a typical bandwidth of one subband which is used in present-day applications.
There are two aspects which will be addressed here and which are of particular relevance for coding applications. The first one is that the overwhelming part of the available psychoacoustical data are obtained with tonal targets (one exception is Jendro, 1992) while in applications the targets consist of white noise. A second aspect concerns the difference in masking behaviour for sinusoidal and for noise maskers. In the coding literature, the difference in masked thresholds between a noise and a tonal target is assumed to be 9 dB (Johnston, 1988), this while Egan and Hake (1950) found a difference of about 15 dB for an on-frequency situation with a tonal target and Jendro (1992) found a similar difference for noise targets (see Fig. 19). Because this assumption can be of great influence on modeling and digital coding further research is done and described in this report using noise targets instead of tonal targets.
The experiments described in this report will therefore concentrate on establishing the masking behaviour of tonal and nontonal maskers using bandpass noise as the target.

Materials and methods

Procedure

For all experiments a 3IFC (three interval forced choice) method was used to establish the masked threshold of the target. The masker was presented in three successive intervals. In one randomly-chosen interval the target was added to the masker. The subject's task was to indicate the interval containing the target. After each response the subject received feedback about whether the answer was correct or incorrect. The sound pressure level of the target was varied adaptively according to a one-up, two-down rule (Levitt, 1971). Such an adaptive algorithm converges at a target level with a 70.7% correct response rate. This adaptive procedure had initial adjusting steps of 8 dB, that were halved after each second reversal, until a stepsize of 1 dB was reached. Then the measurement phase started and from the following eight reversals the median was determined. Each threshold value is the average of four such medians. For an example of an adaptive procedure, see Fig. 3.

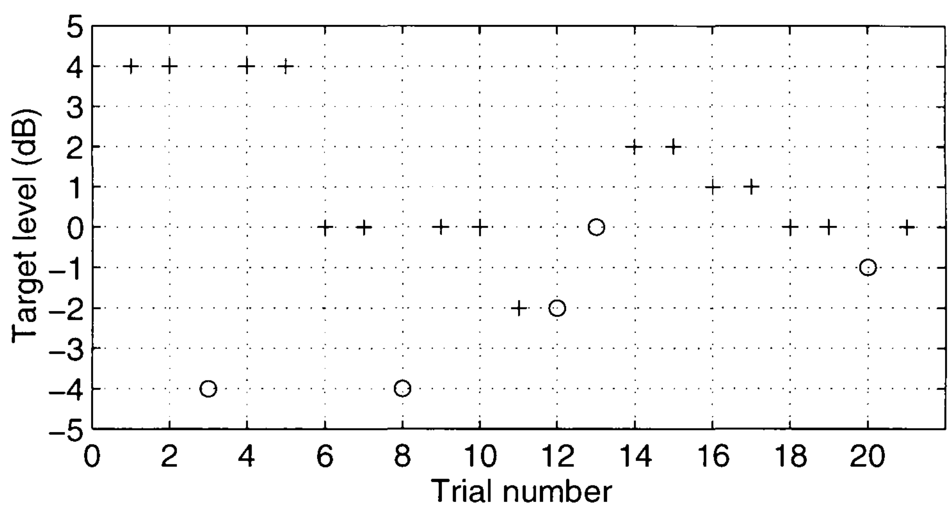

Fig. 3: An example of a part of an adaptive procedure with correct (+) and incorrect (o) answers. Initial level steps are 8 dB, that are halved after each second reversal, until stepsizes of 1 dB are reached.

Stimuli

The target of 300 ms and the masker of 400 ms were presented simultaneously, where the target had a delay of 50 ms in comparison to the masker (see Fig. 4 for a possible trial). A Hanning window with ramp durations of 50 ms was used for masker and target to avoid spectral splatter. The separation between successive intervals was 300 ms and it was 200 ms between the subject's response and the beginning of the next trial. The stimuli were presented diotically over Beyerdynamic DT 990 headphones.

The 300-ms target consisted of frozen noise, while the masker was either a random noise or a sinusoid with or without amplitude modulation. The frozen-noise target consisted of a 750-Hz wide Gaussian-noise band. For each adaptive run an independent target was generated once and copied for every trial.

The 400-ms random-noise masker samples were obtained by randomly selecting a segment from a 2000-ms bandpass-noise buffer. This was done independently for every interval. The bandpass-noise buffer was created in the frequency domain by selecting the frequency range from the Fourier transform of a 2000-ms broadband Gaussian noise. After an inverse Fourier transform, the band-limited noise buffer of 2000 ms was obtained (cf e.g. Breebaart et al., 1998).

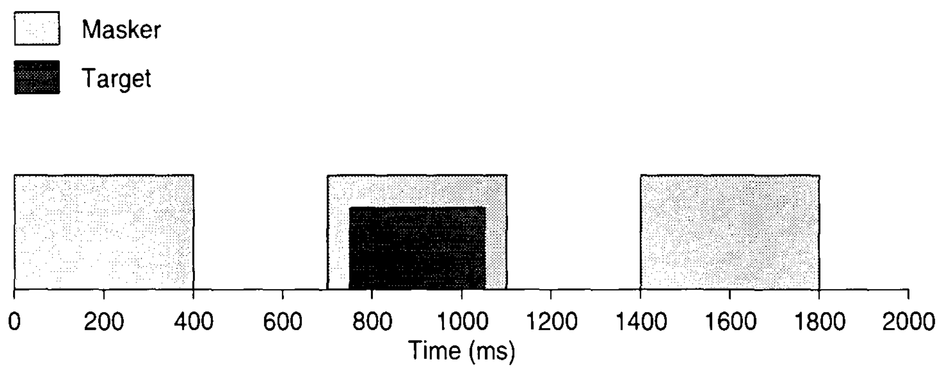

Fig. 4: Timing of an experiment, consisting of three intervals each containing a masker of 400 ms and one randomly-chosen interval containing in addition the target of 300 ms.

All stimuli used in the experiments were generated digitally and converted to analog signals with a two-channel, 16-bit D/A converter at a sampling rate of 48 kHz for experiments 1 and 2a and 32 kHz for experiments 2b, 3 and 4. The experiments were performed in a soundproof listening booth.

Subjects

A pool of six subjects (jb, lb, lf, ch, eh and mv) with normal hearing participated in the experiments, varying in age from 20 to 27 years. The absolute thresholds were measured and for a 4125 Hz signal the thresholds of all six subjects were below 5 dB SPL. All subjects had at least three hours of experience with psychoacoustical experiments except for subject ch who participated in only one experiment. Every experiment was performed by four subjects. Two subjects (lf and eh) participated in all experiments, two (lb and mv) in all but experiment 1 and two subjects participated only in experiment 1. Additional pilot experiments were performed by the author.

Because the results of the subjects did not vary too much only the average results are shown. If not mentioned otherwise the averages are based on the results of four subjects. So each data point in a figure consists of the average and standard deviation of four threshold values.

Experimental results

Experiment 1

This experiment was done to get data on the influence of level and frequency of a sinusoidal masker by masking a noise target. The target always had a bandwidth of 750 Hz and had the same center frequency as the masker. It was expected that the sinusoid masked more at high than at low frequencies, so the thresholds should increase with increasing frequency. This expectation was based on the fact that the critical bandwidth increases with frequency. Thus measured in terms of critical bands the noise target becomes narrower toward higher frequencies and should therefore be masked more easily.
The center frequencies for this on-frequency experiment were 1125, 4125, 6375 and 8625 Hz. The different levels for the masker were 30, 50 and 70 dB SPL.

The results of this experiment can be seen in Fig. 5, together with the average absolute threshold of all four subjects. On the x-axis the center frequencies of the target and masker can be found in Hz, while the y-axis shows the level of the target threshold in dB SPL. The three lines, representing target thresholds for a 30- (downward triangles), 50- (upward triangles) or 70-dB (squares) level of the masker, increase monotonically with frequency. The thresholds increase with an increasing sound pressure level, but not linearly. The strong influence of center frequency in this task is revealed by the fact that the threshold for a 70-dB masker at 1125 Hz is about the same as for the 30-dB masker at 8625 Hz.

At the lowest masker level for two subjects the thresholds increased continuously with the masker frequency, while for the other two a slight decrease was seen towards the highest frequency. This effect was small for the 6375-Hz value but was more clearly seen at 8625 Hz. It is almost certain that this is due to differences in their absolute thresholds. For the absolute thresholds of each of these four subjects, see Fig. 1 in the Appendix.

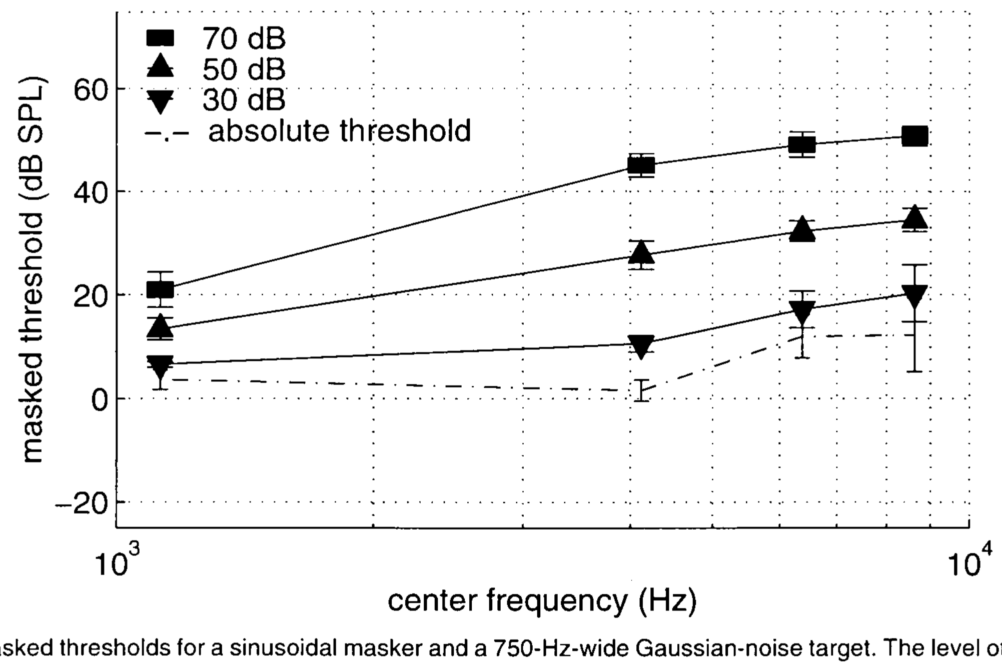

Fig. 5: Masked thresholds for a sinusoidal masker and a 750-Hz-wide Gaussian-noise target. The level of the masker varied between 30 (downward triangles), 50 (upward triangles) and 70 dB SPL (squares) and the used center frequencies were 1125, 4125, 6375 and 8625 Hz. Absolute thresholds are shown by the dashed-dotted line.

Experiment 2

The motivation for the measurements of experiment 2 was to collect data on the influence of envelope fluctuations of the masker in an on-frequency masking situation. This was done in experiment 2a by using a masker that consisted of three sinusoids, 50 Hz separated from each other, e.g. 1075, 1125 and 1175 Hz. The levels of the center frequencies were the same as in experiment 1 (30, 50 or 70 dB SPL) and the sideband level was varied relative to the center component. The relative levels were 0 (black squares), -3 (upward triangles), -13 (downward triangles) and -23 dB (diamonds) with respect to the center component. Two of the subjects measured a -33 dB (white squares) relative level as well. The total levels of the stimuli with the 70-dB center component were respectively: 74.8, 73.0, 70.4, 70.0 and 70.0 dB SPL. The center frequencies, for the target as well as for the masker, were 1125, 4125, 6375 and 8625 Hz. The target was a 750-Hz wide Gaussian noise. In Fig. 6a, b, c and d envelope fluctuations are shown for the maskers used in experiment 2a. The four panels show the waveforms for relative sideband levels of 0, -3, -13 and -23 dB.

The results for the three sound pressure levels of the center component are shown in Fig. 7a, b and c. This experiment was also performed by the author as a pilot test with the three sinusoids 10 Hz separated from each other, instead of 50 Hz. This was done for sideband levels of 3, 13, 23 and 33 dB below the center component. The results can be found in Fig. 8a, b and c.

The lower the sideband levels of the sinusoidal masker of experiment 2a were, the less the modulation depth, except for the 0-dB and the -3-dB relative level (see also Fig. 6a, b, c and 6d), and the smaller the bandwidth of the masking pattern. The expected effect of the envelope fluctuations, based on data obtained with sinusoidal targets, was that the more the masker was modulated, the lower the masked thresholds would be (see Nelson and Schroder, 1996).

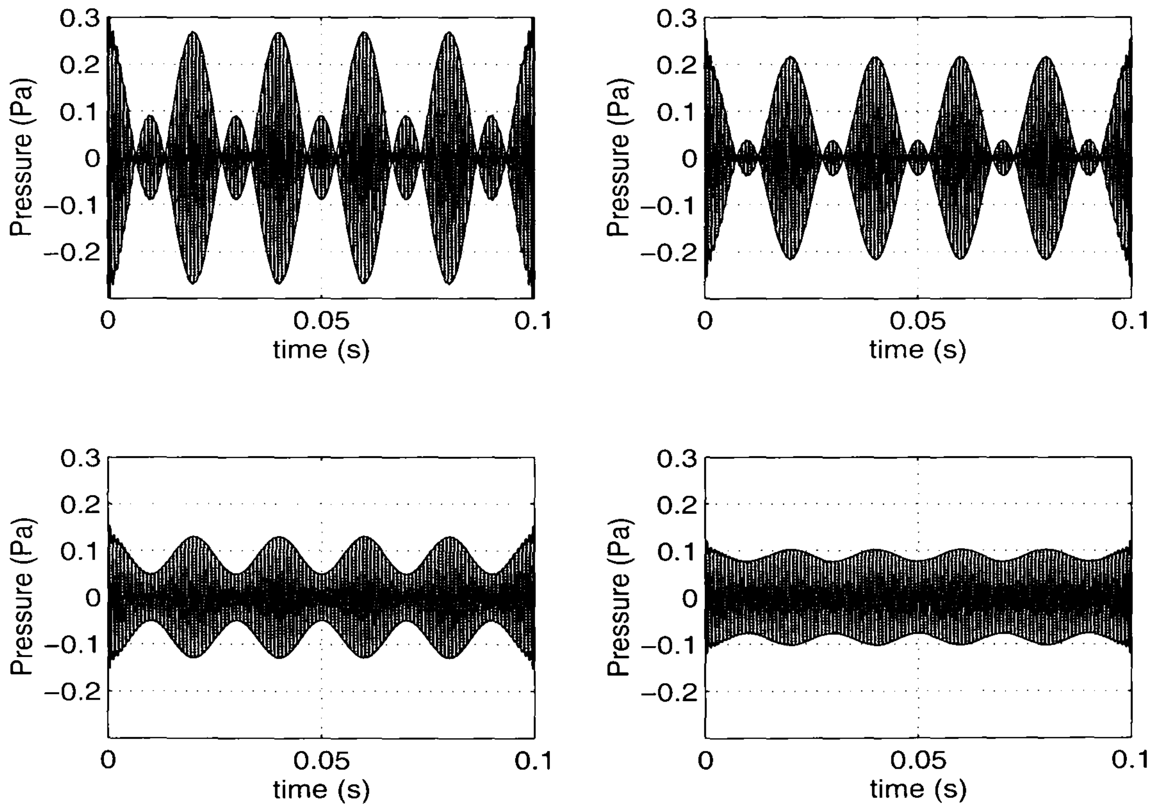

Fig. 6a, b, c and d: Envelope fluctuations in a sinusoidal masker consisting of three sinusoids with the frequencies 1075, 1125 and 1175 Hz. The center frequency of 1125 Hz had a level of 70 dB SPL, while the sidebands had a level of respectively 70, 67, 57 and 47 dB SPL each.

The results of experiment 2a can be found in Fig. 7a, b and c, where the x-axis represents the center frequency of the masker and target. The y-axis shows the masked threshold of the target. The results of the experiments with the same level of the center component are plotted in the same figure. In Fig. 7a, b and c these levels are 70, 50 and 30 dB SPL. If the results of experiment 2a were plotted differently, for instance the 0-dB relative levels of 70, 50 and 30 dB in one graph, then the shape of the graphs would have been comparable to those of experiment 1.
The thresholds of experiment 2a decrease with a decreasing degree of modulation. The levels of the sidebands determine this and when these levels are low, the degree of modulation is low as well. For the two highest sideband levels the modulation depth does not increase anymore (see Fig. 6a and b). The single sinusoid (a result of experiment 1) is an unmodulated masker and has similar results as the maskers with 23 and 33 dB lower relative sideband levels.

The results of the pilot experiment, with 10-Hz separated sideband levels, can be found in Fig. 8a, b and c. The masked thresholds for different sideband levels are all comparable, only the 1125-Hz -3-dB relative level has a higher threshold. No increase is seen for an increase in modulation, except for the -3-dB relative sideband level of the 70-dB center component. All these conditions are only measured once by subject eh.

In experiment 2b, of which the results can be found in Fig. 9, a multiplied-noise was used as masker with a bandwidth of 100 Hz. Multiplied noise was generated by multiplying a Gaussian lowpass noise with a 50-Hz cutoff frequency with a sinusoid of either 1125, 4125, 6375 or 8625 Hz. This resulted in a bandpass noise with 100-Hz bandwidth and a center frequency which was equal to the center frequencies of the 3-tone complexes in experiment 2a. The masker had a level of 74.8 dB SPL, because this agreed with the maximum masker level in experiment 2a (the masker with the 70-dB sidecomponents, the 0-dB relative level). This experiment was also measured with a Gaussian-noise masker of 74.8 dB instead of a multiplied noise, but the results were exactly the same and are therefore not plotted. Both these experiments were only measured by subject eh.
The noise thresholds were expected to be higher than those of the sinusoids, because it is easier to discriminate a noise target from a masker that is less fluctuating in amplitude and spectrum. That is why for multiplied noise the masked thresholds were expected to be lower than for Gaussian noise. All thresholds were expected to increase with increasing masker level and masker frequency.

In Fig. 9 the results of experiment 2b (black symbols) can be found and also results of experiment 2a (open symbols), namely for sideband levels that are equal to the center component. All maskers used to get the results of Fig. 9 had a total level of 74.8, 54.8 or 34.8 dB.
The masked thresholds for experiment 2b, the multiplied-noise experiment, are all lower than the masked thresholds for experiment 2a. The differences varied between 0 and 7 dB. The shape of the graph is comparable to experiment 1 and 2a, because the thresholds for the 1125-Hz center frequency increase less with the masker level than for the higher center frequencies. Also the thresholds increase monotonically with frequency.

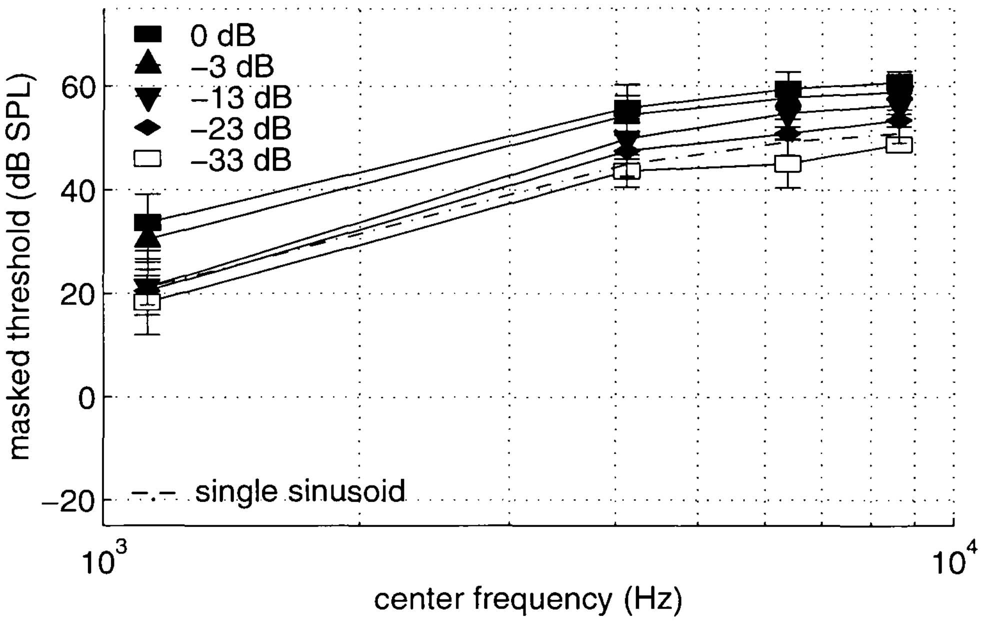

Fig. 7a: Masked thresholds of a sinusoidal masker consisting of three sinusoids, 50 Hz separated from each other, and a 750-Hz-wide Gaussian-noise target. The center frequencies were 1125, 4125, 6375 and 8625 Hz and the center component had a level of 70 dB SPL. The levels of the sidebands relative to the center frequency were 0 (black squares), -3 (upward triangles), -13 (downward triangles), -23 (diamonds) and -33 dB (white squares). The thresholds for a single sinusoid are also shown (dashed-dotted line) (results of experiment 1).

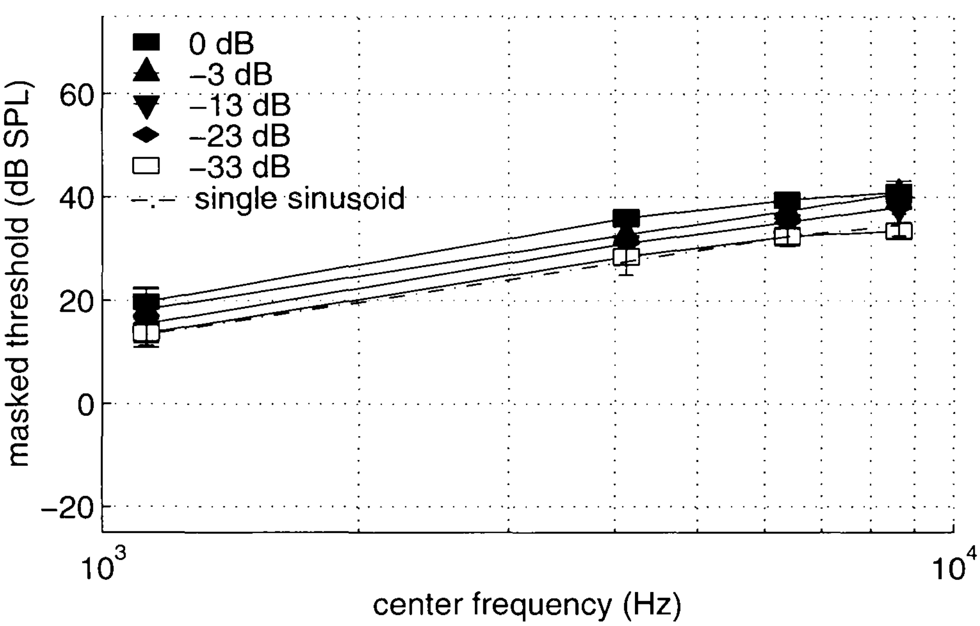

Fig. 7b: Same format as Fig. 7a, only the level of the sinusoidal center frequencies was 50 dB SPL.

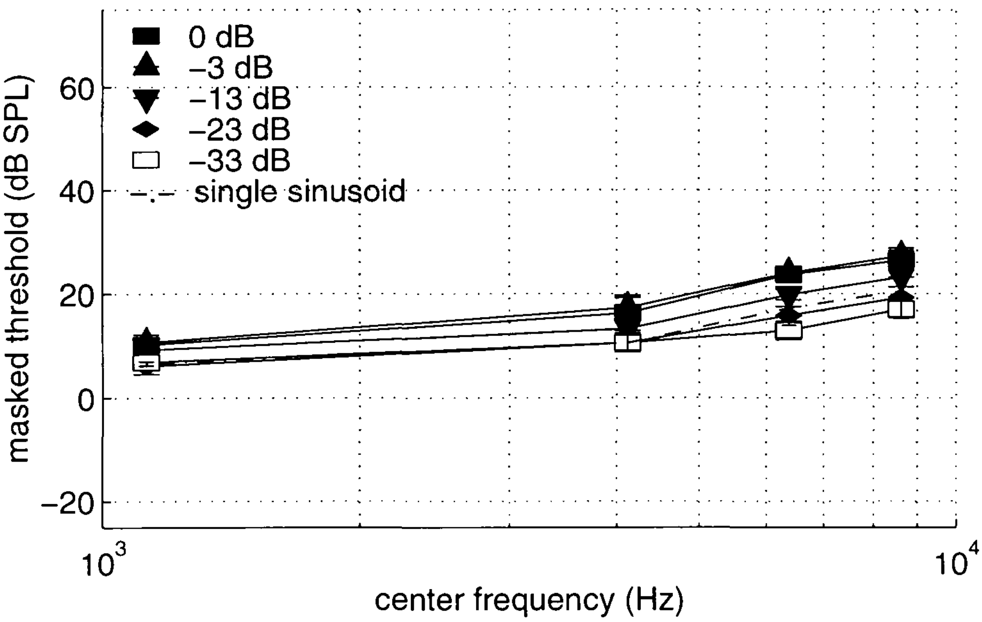

Fig. 7c: Same format as Fig. 7a, only the level of the sinusoidal center frequencies was 30 dB SPL.

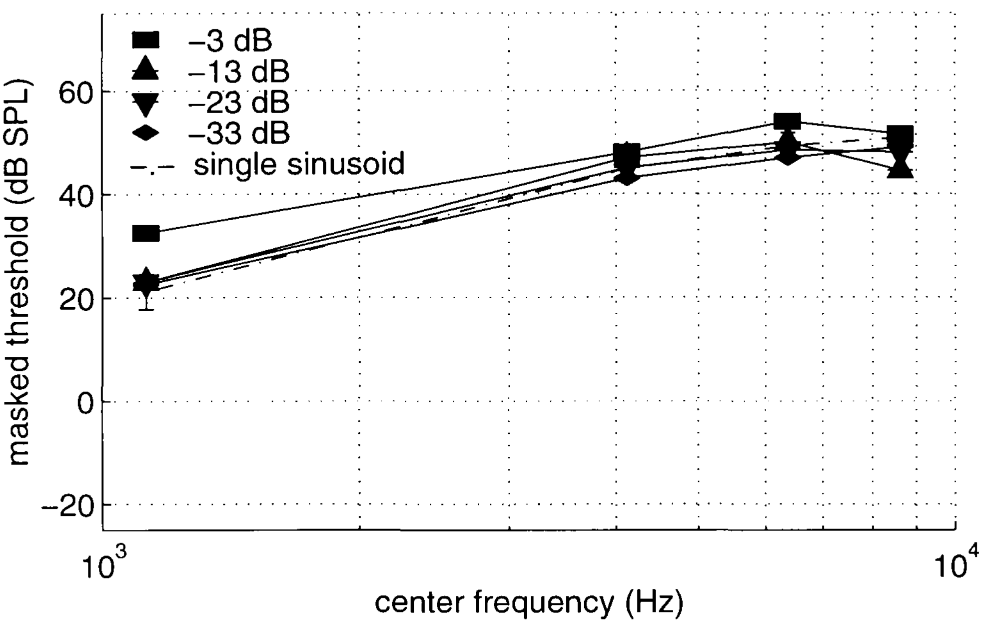

Fig. 8a: Masked thresholds of a sinusoidal masker consisting of three sinusoids, 10 Hz separated from each other, and a 750-Hz-wide Gaussian-noise target. The frequencies of the center component were 1125, 4125, 6375 and 8625 Hz and it had a level of 70 dB SPL. The levels of the sidebands were relative to the center frequency: -3 (black squares), -13 (upward triangles), -23 (downward triangles) and -33 dB SPL (diamonds). The thresholds for a single sinusoid are also shown (dashed-dotted line) (results of experiment 1). This pilot experiment was only measured once by one subject.

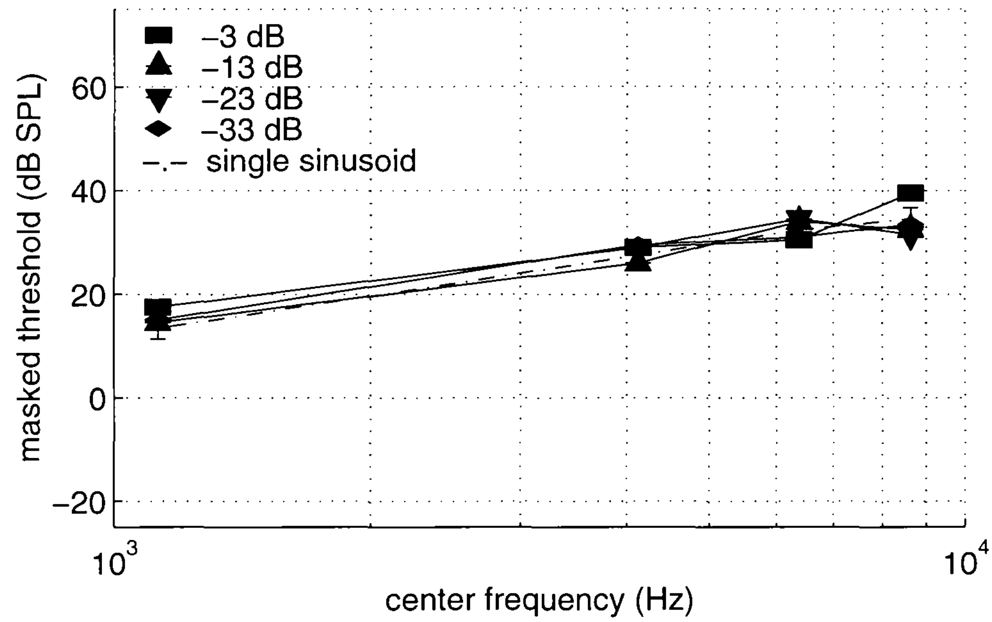

Fig. 8b: Same format as Fig. 8a, only the level of the sinusoidal center component was 50 dB SPL.

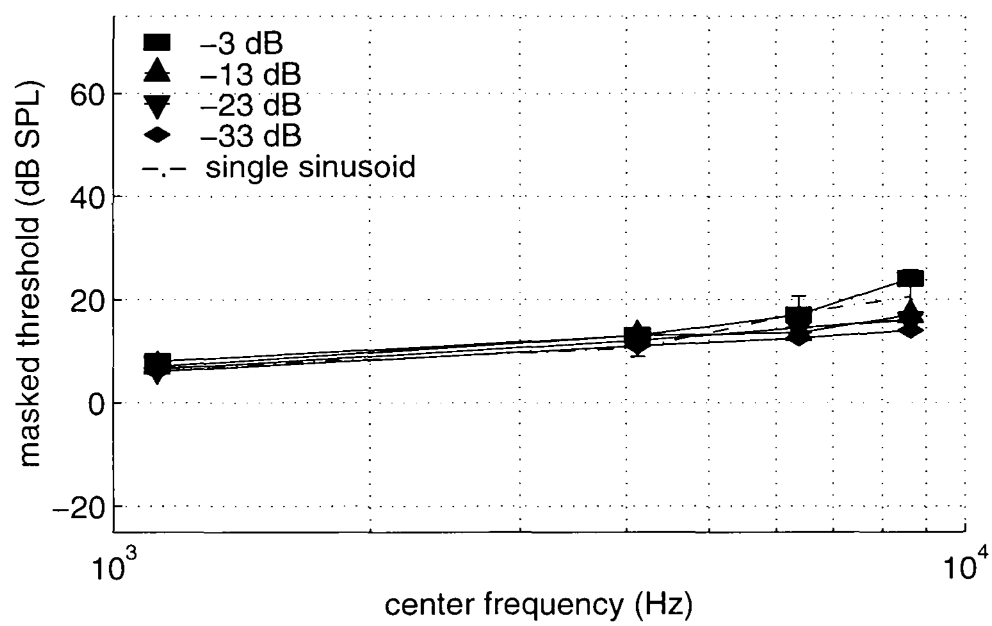

Fig. 8c: Same format as Fig. 8a, only the level of the sinusoidal center component was 30 dB SPL.

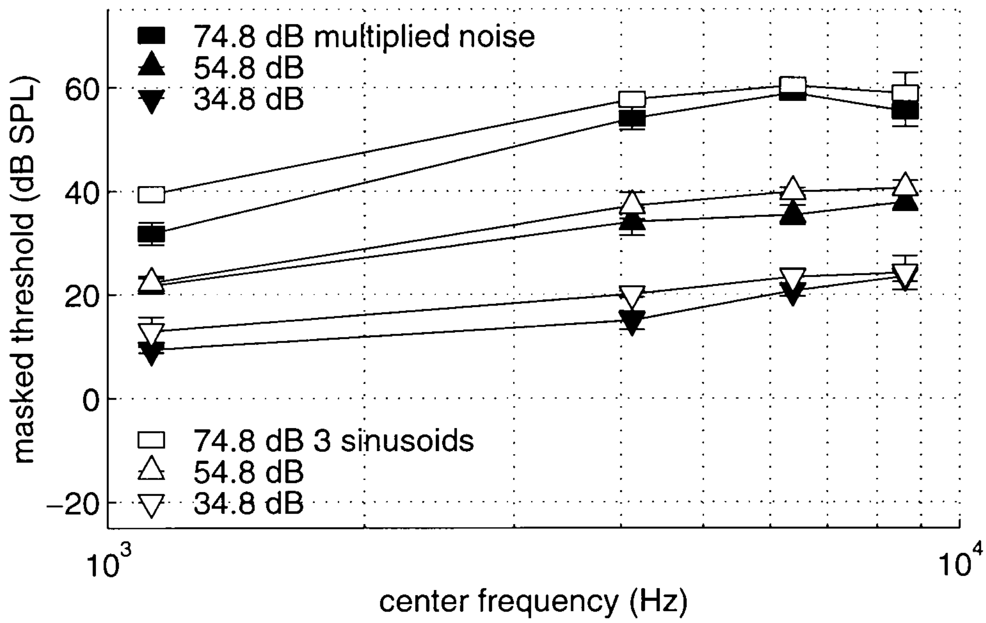

Fig. 9: Masked thresholds, for one subject only, of a multiplied-noise masker with a center frequency of 1125, 4125, 6375 and 8625 Hz and a level of 74.8 (black squares), 54.8 (black upward triangles) and 34.8 dB SPL (black downward triangles). A 750-Hz-wide Gaussian-noise target was used. In addition masked thresholds are shown for a masker consisting of three sinusoids with a relative sideband level of 0 dB, center frequencies of 1125, 4125, 6375 and 8625 Hz and overall levels of 74.8 (white squares), 54.8 (white upward triangles) and 34.8 dB SPL (white downward triangles) (results of experiment 2a).

Experiment 3

The thresholds of experiment 2a, with a modulated sinusoidal masker, were higher than those of experiment 2b, with a multiplied-noise masker. That was unexpected, because the envelope fluctuations of the sinusoidal masker were periodic, and those of the multiplied-noise masker were aperiodic. Experiment 3 was done to find out more about these differences in masking behaviour of a sinusoidal masker versus a noise masker. Instead of a multiplied-noise masker a Gaussian-noise masker was used. Earlier experiments have shown that the differences in masked thresholds between a Gaussian-noise masker and a sinusoidal masker for a sinusoidal target with the same frequency are about 15 dB (Egan and Hake, 1950).

In experiment 3 a 100-Hz wide Gaussian-noise masker was used with a level of 70 dB. The target consisted of a 750-Hz-wide Gaussian noise. The used center frequencies, for target and masker, were 1125, 4125, 6375 and 8625 Hz. Only two subjects participated in this experiment. The results are compared with results of experiment 1 in Fig. 10, but only results of the same two subjects are plotted.

The results of experiment 3 seem to converge to an asymptotic value of 53 dB SPL with increasing center frequency. These results also show that the thresholds measured with a Gaussian-noise masker (squares) are higher than those measured with a sinusoidal masker (dashed-dotted line). The differences are small, they vary between 1.5 at high and 8.5 dB at low frequencies. The shape of the results of experiment 1 and 3 are comparable, only the differences in thresholds decrease with increasing center frequency.

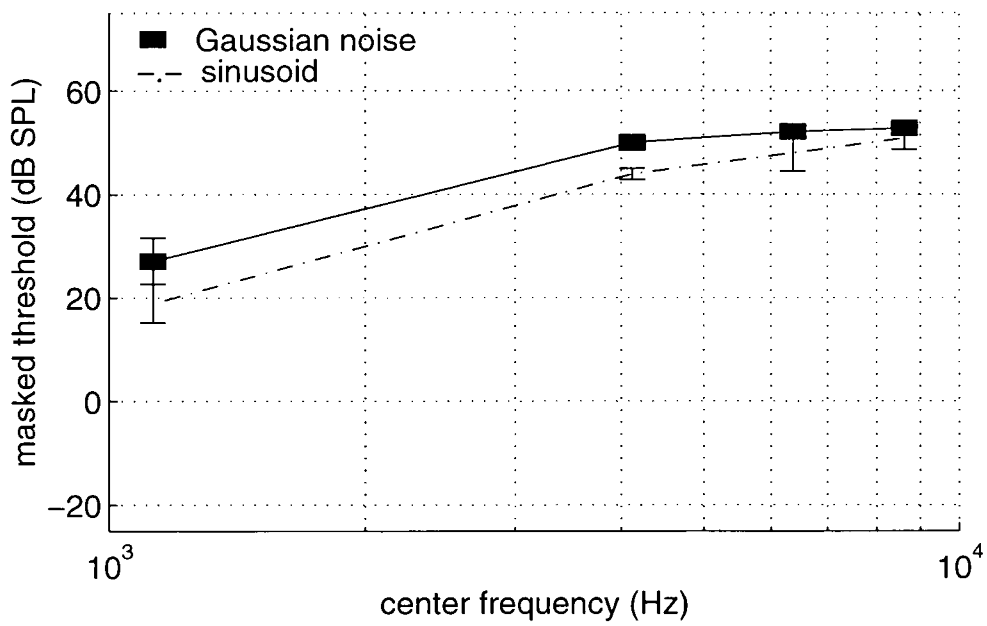

Fig. 10: Masked thresholds of a 100-Hz-wide Gaussian-noise masker of 70 dB SPL for center frequencies of 1125, 4125, 6375 and 8625 Hz and a 750-Hz-wide Gaussian-noise target. The dashed-dotted curve shows masked thresholds for a sinusoidal masker from experiment 1. These data are from the subjects lf and eh only.

Experiment 4

The motivation for experiments 4a and b was to get data on differences between sinusoidal and noise maskers in an off-frequency masking situation. Another reason was that if the frequency of the target or masker is held constant and the masker or target is varied then the shape of the masking pattern can be estimated. In addition the influence of the masker bandwidth on the masking pattern was studied.
In experiment 4a five different maskers were used, a sinusoidal masker (dashed-dotted line) and four Gaussian-noise maskers with different bandwidths: 10 (squares), 100 (upward triangles), 300 (downward triangles) and 750 Hz (diamonds). The center frequencies for the masker were 1125 and 6375 Hz at a level of 70 dB SPL. The 750-Hz-wide Gaussian-noise target had the following center frequencies: 375, 1125, 1875 and 3375 Hz for the 1125-Hz masker and 5625, 6375, 7125 and 8625 Hz for the 6375-Hz masker.
Two subjects participated in additional experimental conditions for the sinusoidal masker with intermediate target frequencies of 1375 and 1625 Hz for subject lf (see Fig. 12b) and 1250, 1325, 1375, 1425 and 1625 Hz for subject eh (see Fig. 12a). One subject also measured 875, 1000, 1250 and 1375 Hz for the 100-Hz Gaussian-noise target with the 1125-Hz Gaussian-noise masker (see also Fig. 12a).

In Fig. 11a the results for the 1125-Hz masker can be found and in Fig. 11b those for the 6375-Hz masker of experiment 4a.
With increasing masker bandwidth the masked thresholds also increase. When comparing the 10-Hz and the 750-Hz maskers, the differences range from 5 to 40 dB.
The thresholds for the 10-Hz-wide Gaussian-noise masker appear to be slightly different for the 1125 versus 6375-Hz values. While for the 1125-Hz masker, the 10-Hz curve always lies below the 100-Hz curve, the two cross for the 6375-Hz masker (see Fig. 11b). This crossing, however, is due to the fact that the 100-Hz data were measured by 4 subjects and those for 10 Hz only by 2 subjects. If the graph was plotted only for these two subjects than the threshold curves would have increased with increasing bandwidth for all center frequencies.
All curves reach a maximum threshold at the on-frequency situation, except for the sinusoidal

masker with a center frequency of 1125 Hz. Here the peak for all four subjects is found at 1875 Hz. In order to better localize the maximum in the threshold curves, two subjects performed additional measurements using intermediate target frequencies (see Fig. 12a and b). For the sinusoidal masker, the region of maximum threshold was 1325 Hz to 1625 Hz. For the 100-Hz wide Gaussian noise, the maximum occurred at 1375 Hz.

The difference between experiment 4a and 4b is that in 4a, the target center frequency was variable and that the masker frequency was fixed while in 4b, the target frequency was constant and the masker frequency was variable.

In Fig. 13a and b the results of experiment 4b can be found, this experiment was measured by the subjects lf and eh only. Two different masker types were used, a sinusoidal masker (dashed-dotted line) and a 100-Hz-wide Gaussian-noise masker (triangles). Since in this figure the masker freqency is plotted on the x-axis, the shape of the masking pattern is mirrored along 1125 Hz. The results all have a peak at the on-frequency value. On a linear scale the slopes towards high frequencies are less steep than those towards low frequencies. The thresholds for the 6375-Hz target are about 10 to 30 dB higher than for the 1125-Hz target for both the Gaussian-noise and the sinusoidal masker.

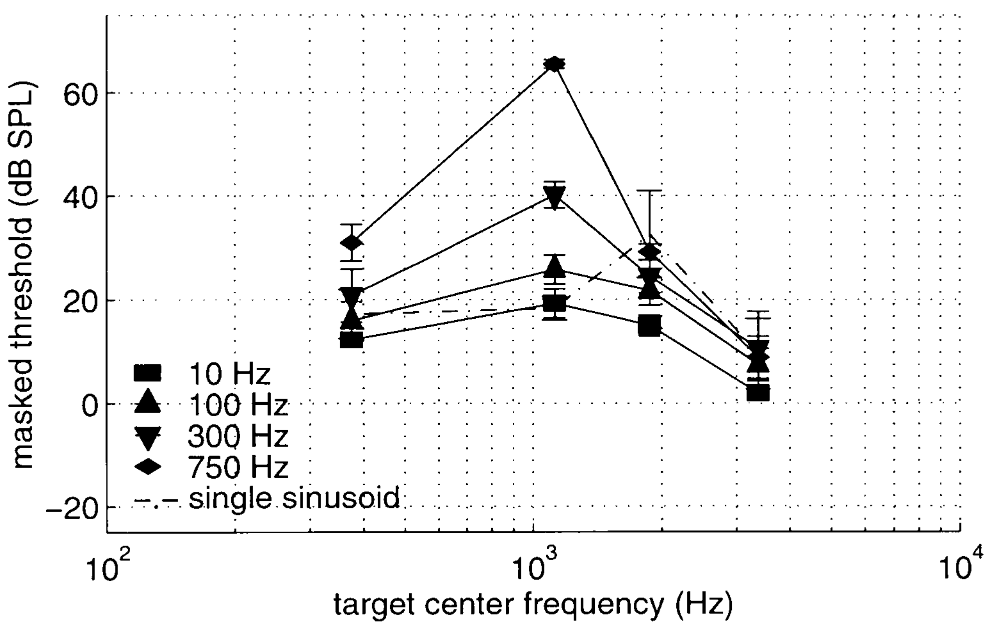

Fig. 11a: Masked thresholds of a Gaussian-noise masker with a center frequency of 1125 Hz and a level of 70 dB SPL. The noise-masker had a variable bandwidth of 10 (squares), 100 (upward triangles), 300 (downward triangles) or 750 Hz (diamonds). Also thresholds of a single sinusoidal masker are shown (dashed-dotted line). A 750-Hz-wide Gaussian-noise target was used with center frequencies of 375, 1125, 1875 and 3375 Hz. The 10-Hz condition was measured by the subjects lf and eh and the 750-Hz condition only by subject eh. Other bandwidths were measured by four subjects.

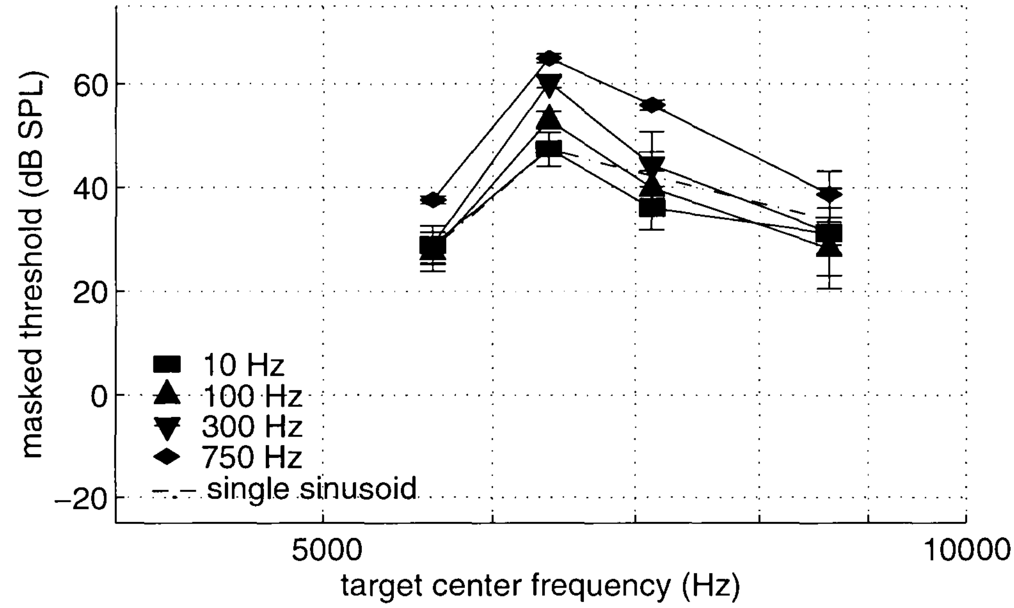

Fig. 11b: Same format as in Fig. 11a, only the center frequency of the masker was 6375 Hz and the center frequencies of the target were 5625, 6375, 7125 and 8625 Hz.

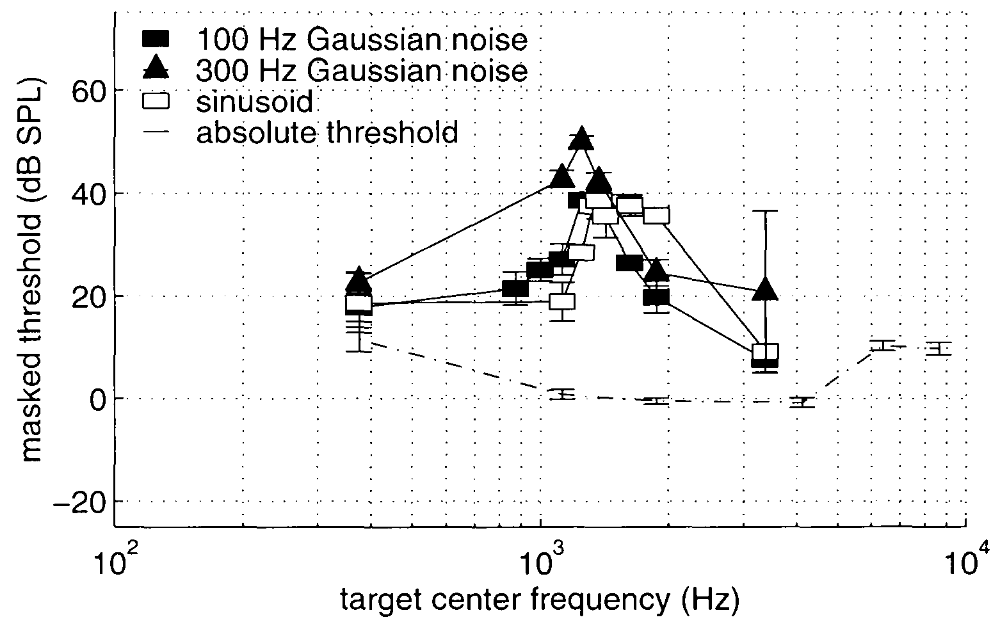

Fig. 12a: Masked thresholds, measured by subject eh, of a Gaussian-noise masker with a center frequency of 1125 Hz and a level of 70 dB SPL. The noise-masker had a bandwidth of 100 Hz (black squares) or 300 Hz (upward triangles). In addition thresholds of a sinusoidal masker are shown (white squares). Absolute thresholds are presented in the figure by the dashed-dotted line.

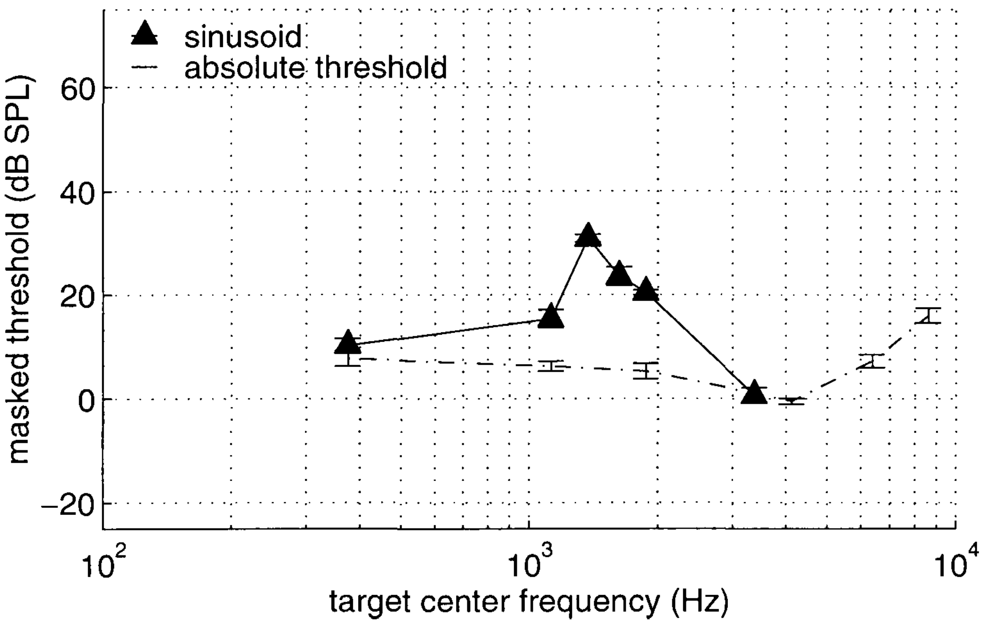

Fig. 12b: Masked thresholds, measured by subject lf, of a sinusoidal masker with a center frequency of 1125 Hz and a level of 70 dB SPL (triangles). Absolute thresholds are presented in the figure by the dashed-dotted line.

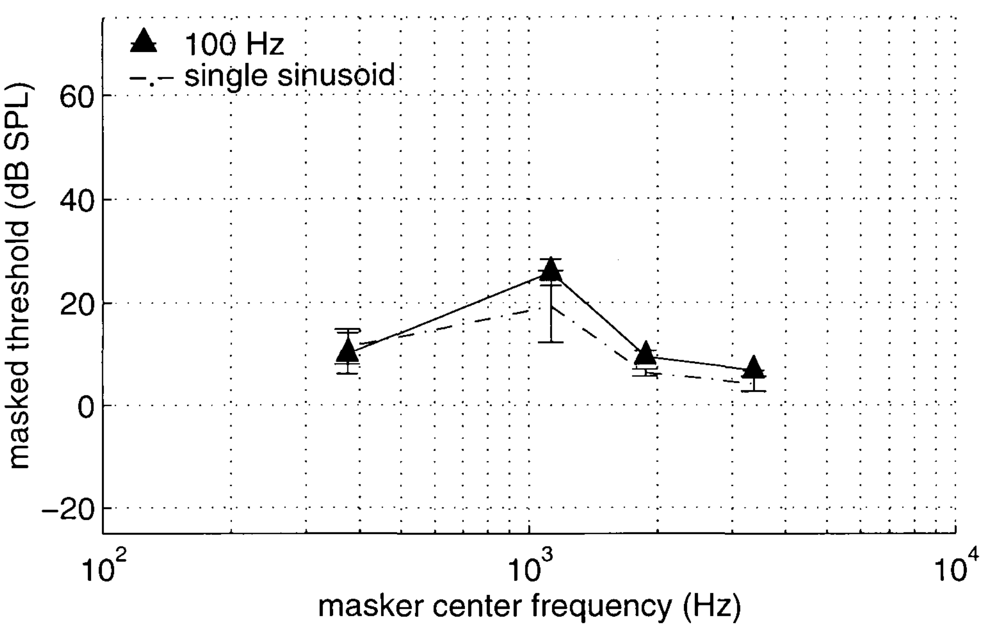

Fig. 13a: Masked thresholds of a 750-Hz-wide noise target with a center frequency of 1125 Hz and a 100-Hz-wide Gaussian-noise masker with a level of 70 dB SPL. The used masker center frequencies were 375, 1125, 1875 and 3375 Hz. Also thresholds of a single sinusoidal masker are shown (dashed-dotted line). These data are from the subjects lf and eh only.

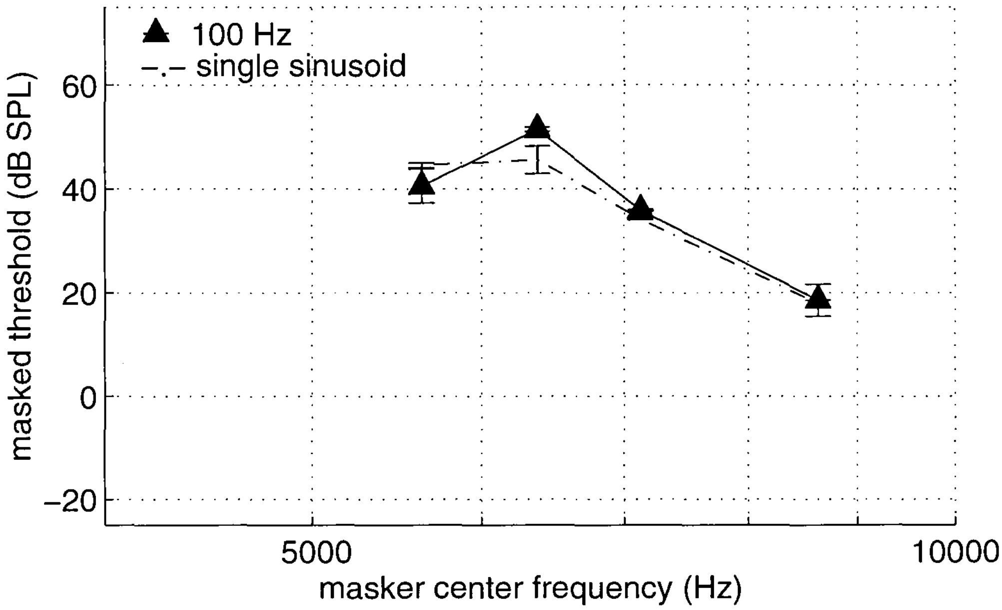

Fig. 13b: Same format as in Fig. 13a, only the center frequency of the target was 6375 Hz and the center frequencies of the masker were 5625, 6375, 7125 and 8625 Hz.

Modeling results

The model used is the multi-channel model described by Dau et al. (1996a, b). Readers are referred to these articles for any further information.
The modeling results presented here are calculated for the same conditions and with the same variables as for the experimental results, in order to be able to compare the predictions of the model with the results of subjects. For that reason the precise explanation of the experiments can be found in the previous section. In all the figures shown here the left graphs represent the experimental results and the right graphs the modeling results.

Experiment 1

The experimental as well as the modeling results of experiment 1 can be found in Fig. 14. The used center frequencies for this on-frequency experiment were 1125, 4125, 6375 and 8625 Hz and they are shown on the x-axis in the graph. On the y-axis the masked thresholds can be found in dB SPL. The different levels for the masker were 30 (downward triangles), 50 (upward triangles) and 70 dB SPL (squares). The target consisted of a 750-Hz-wide Gaussian noise.

The masked thresholds of the modeling results increase with increasing center frequency and level, just like the experimental results. In general the thresholds of the model are 3 to 20 dB higher than the comparable thresholds of the experiments. Also the thresholds of the model seem to increase more linearly with an increase in sound pressure level than the experimental results. If the 8625-Hz values for the 30- versus the 70-dB level are compared, then the thresholds increase about 38 dB for the model and about 32 dB for the experiments.

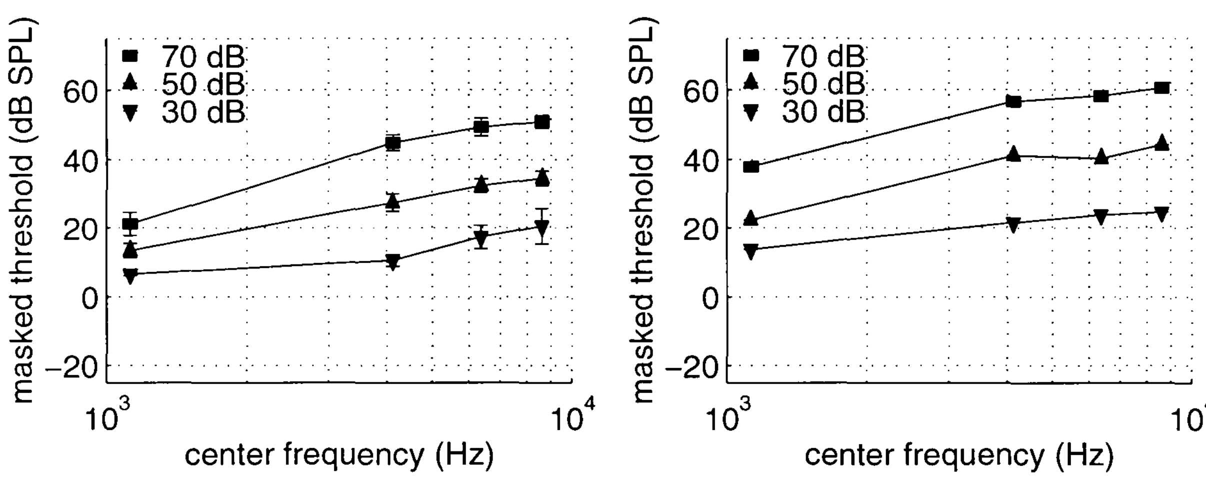

Fig. 14: The left panel shows the experimental results and the right panel the modeling results; the masked thresholds for a sinusoidal masker and a 750-Hz-wide Gaussian-noise target. The level of the masker varied between 30 (downward triangles), 50 (upward triangles) and 70 dB SPL (squares) and the used center frequencies were 1125, 4125, 6375 and 8625 Hz (the experimental results are a copy of Fig. 5).

Experiment 2

In Fig. 15a, b and c the results of experiment 2a can be found. The masker consisted of three sinusoids, 50 Hz separated from each other. The center components had a sound pressure level of 30, 50 or 70 dB, and the sidebands had a relative level of 0 (black squares), -3 (upward triangles), -13 (downward triangles), -23 (diamonds) and -33 (white squares) dB. The used center frequencies, for the target as well as for the masker, were 1125, 4125, 6375 and 8625

Hz. The target was a 750-Hz-wide Gaussian noise.

The masked thresholds of the modeling results of experiment 2a (for the 30, 50 and 70 dB center component) increase with an increasing center frequency, like for the experimental results. But they hardly increase with an increasing sideband level (the maximum increase is about 8 dB), while in the experimental results the maximum increase is about 20 dB.
For the 70-dB center component the thresholds are higher for the modeling results than for the experimental results, this difference is very small for the 50-dB and the 30-dB center components.
The shapes of Fig. 15a, b and c vary, because the amount by which the thresholds increase with increasing center frequency, decreases. For the 70-dB center component of the masker, this effect is largest, while this is smallest for the 30-dB value. For instance the difference in threshold at 70 dB for the 1125-Hz versus the 8625-Hz value is about 20 dB, while this is only about 10 to 15 dB for the 30-dB center component. And this is true for the experimental as well as for the modeling results.
The single sinusoid (dashed-dotted line) has a level of 70.0 dB and thus can be compared to the -23 and -33 dB relative level because these stimuli also have an overall level of 70.0 dB SPL. Because these three maskers have about the same thresholds it is shown that these low values of modulation depth do not have an influence here.

The results of the multiplied-noise experiment are shown in Fig. 16 together with results of experiment 2a, the three sinusoids with a 0-dB relative sideband level. The levels of the masker were 74.8, 54.8 or 34.8 dB SPL for the multiplied noise as well as for the sinusoids. (The pilot experiment done with a 100-Hz-wide Gaussian-noise masker of 74.8 dB SPL can be found in Fig. 8a, b, and c.) The used center frequencies were 1125, 4125, 6375 and 8625 Hz.

A comparison of the experimental and modeling results in Fig. 16 reveals that the results for the sinusoidal maskers are comparable. The modeling results are 0 to 3 dB higher than the experimental results. Bigger differences can be seen for the results with the multiplied-noise masker. The thresholds are much higher for the modeling results than for the experimental results and the differences range from 5 dB to 20 dB. If the shapes of the two graphs are compared, then no difference is seen.

Table 1 shows the modeling and experimental results of a 74.8-dB multiplied-noise and a 74.8-dB Gaussian-noise masker. For the experimental results the thresholds for the two maskers are very close to each other. Also the thresholds of these two maskers are comparable for the modeling results, but not if they are compared to the experimental results. Then the thresholds of the modeling results are much higher, ranging from 6.6 dB to 18.1 dB, with bigger differences for lower frequencies.

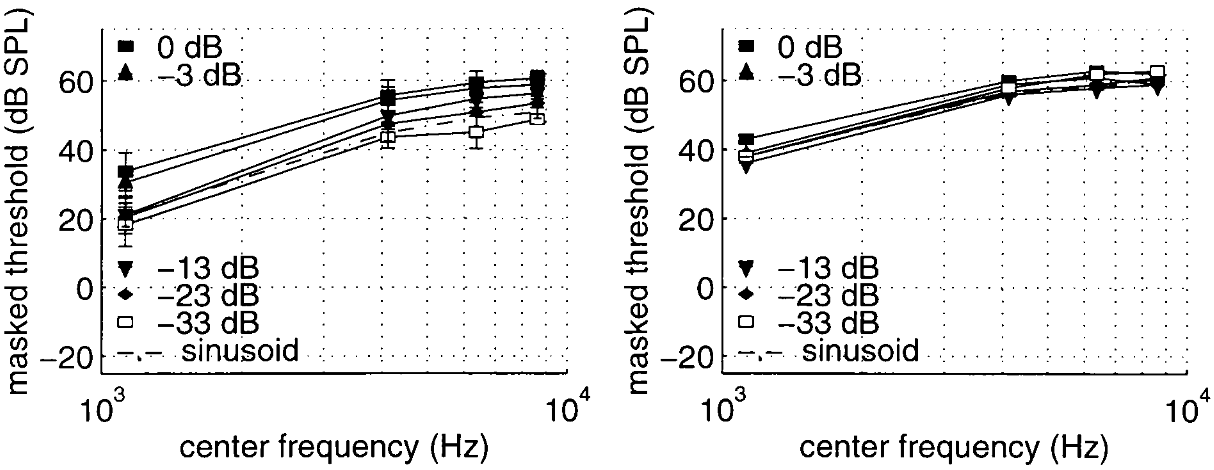

Fig. 15a: The left panel shows the experimental results and the right panel the modeling results; the masked thresholds of a sinusoidal masker consisting of three sinusoids, 50 Hz separated from each other, and a 750-Hz-wide Gaussian-noise target. The center components were 1125, 4125, 6375 and 8625 Hz and they had a level of 70 dB SPL. The levels of the sidebands relative to the center component were: 0 (black squares), -3 (upward triangles), -13 (downward triangles), -23 (diamonds) and -33 dB (white squares). The thresholds for a single sinusoid are also shown (dashed-dotted line) (see Fig. 14 for the sinusoid of the modeling results, the experimental results are a copy of Fig. 7a).

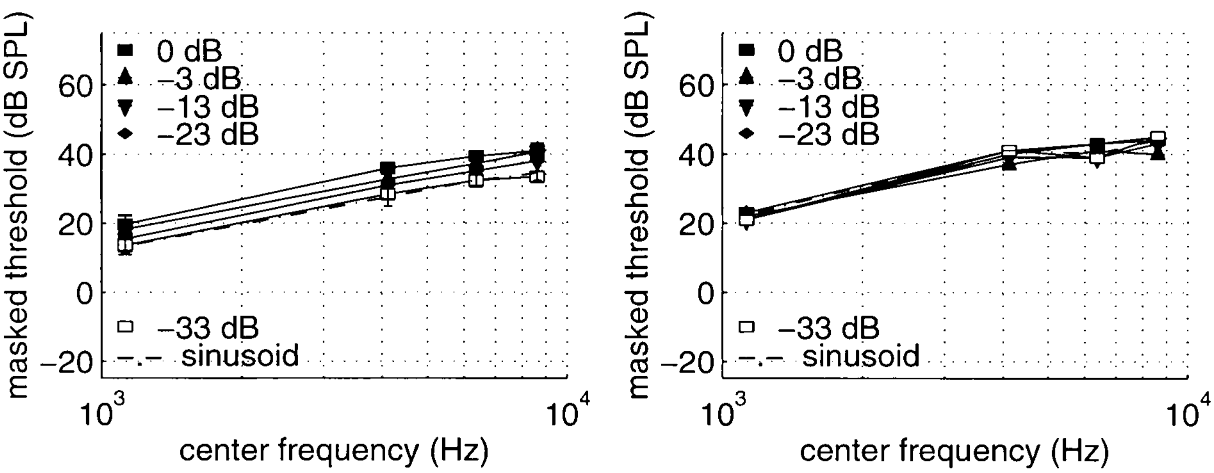

Fig. 15b: Same format as Fig. 15a, only the level of the center component was 50 dB SPL (the experimental results are a copy of Fig. 7b).

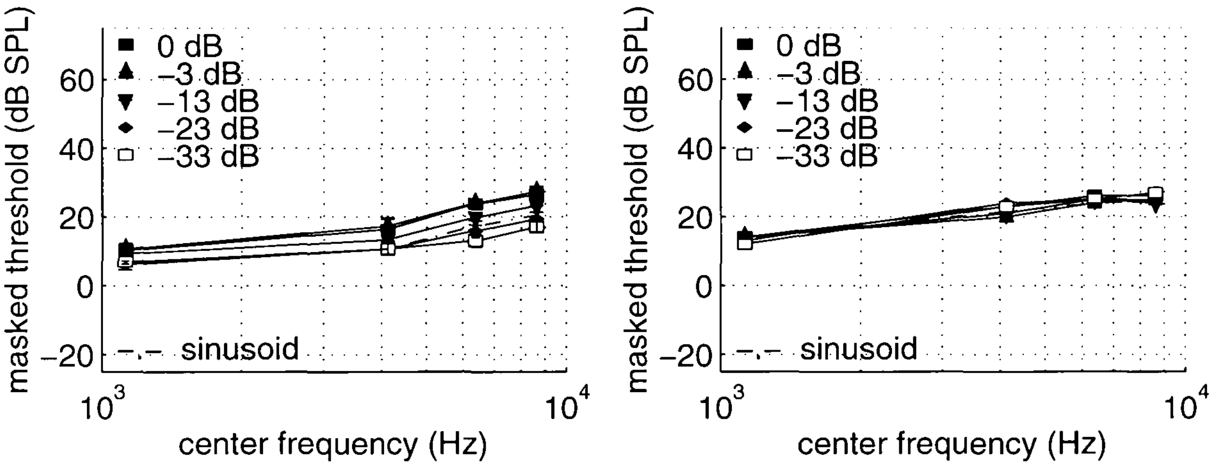

Fig. 15c: Same format as Fig. 15a, only the level of the center component was 30 dB SPL (the experimental results are a copy of Fig. 7c).

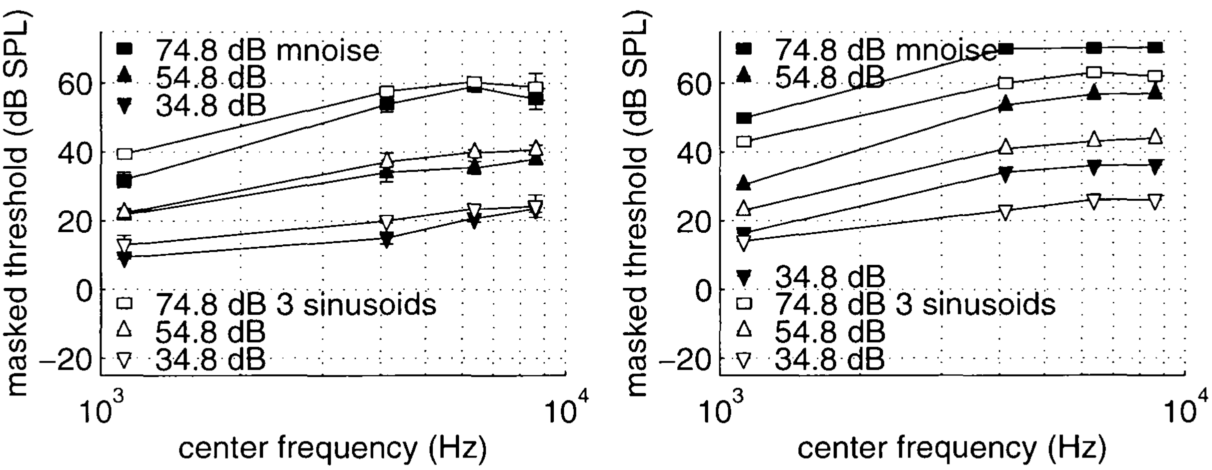

Fig. 16: The left panel shows the experimental results and the right panel the modeling results of masked thresholds of a multiplied-noise masker (mnoise) with a center frequency of 1125, 4125, 6375 and 8625 Hz and a level of 74.8 (black squares), 54.8 (black upward triangles) and 34.8 dB SPL (black downward triangles). A 750-Hz-wide Gaussian-noise target was used. In addition masked thresholds are shown for a masker consisting of three sinusoids with a relative sideband level of 0 dB. Center frequencies of 1125, 4125, 6375 and 8625 Hz and overall levels of 74.8 (white squares), 54.8 (white upward triangles) and 34.8 dB SPL (white downward triangles) (these are a copy of Fig. 9, the results of experiment 2a) were used. All experimental results are for one subject only.

	Experiment	Experiment	Model	Model
CF (Hz)	mnoise	Gnoise	mnoise	Gnoise
1125	31.8	28.3	49.9	44.1
4125	53.9	54.4	70.0	61.0
6375	58.9	56.9	70.1	69.4
8625	55.4	55.3	70.3	70.0

Table 1: The second and third columns show the experimental results and the two columns at the right side show the modeling results; the masked thresholds of a multiplied-noise masker (mnoise) or a Gaussian-noise masker (Gnoise). They both had center frequencies of 1125, 4125, 6375 and 8625 Hz (indicated in the first column) and a level of 74.8 dB SPL. A 750-Hz-wide Gaussian-noise target was used.

Experiment 3

In this on-frequency experiment a 100-Hz-wide Gaussian-noise masker was used with a level of 70 dB. The used center frequencies were 1125, 4125, 6375 and 8625 Hz. The results are compared with experiment 1, which had a sinusoidal masker, and are shown in Fig. 17.

The masked thresholds of the modeling results are higher than those of the experimental results, with differences ranging from 3 to 10 dB for the Gaussian noise and 7 to 20 dB for the sinusoid. The model predicts the sinusoid to mask slightly more than the Gaussian noise, while the experimental results indicate the opposite.

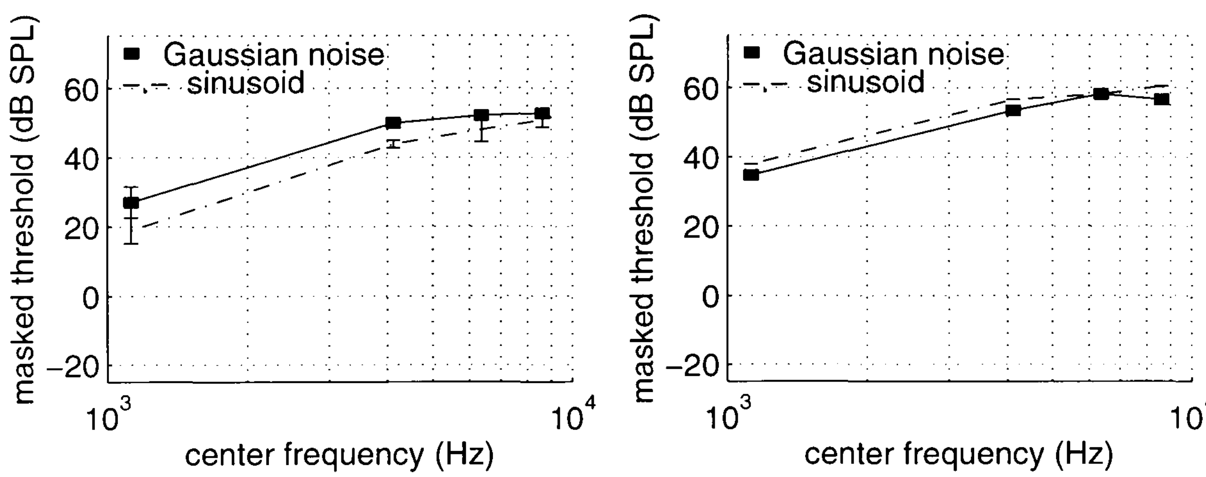

Fig. 17: The left panel shows the experimental results and the right panel the modeling results of masked thresholds of a 100-Hz-wide Gaussian-noise masker of 70 dB SPL for center frequencies of 1125, 4125, 6375 and 8625 Hz and a 750-Hz-wide Gaussian-noise target. Also masked thresholds of a single sinusoid are shown (see Fig. 15a for the sinusoid of the modeling results, the experimental results are a copy of Fig. 10).

Experiment 4

The masker in this experiment had a level of 70 dB SPL and a center fequency of 1125 or 6375 Hz. This masker consisted either of a sinusoid (dashed-dotted line) or of a Gaussian noise with the following bandwidths: 10 (black squares), 50 (upward triangles), 100 (downward triangles), 300 (diamonds), 500 (white squares) or 750 Hz (white upward triangles). (For the experimental results only the 10, 100, 300 and 750-Hz-wide maskers were used.) The 750-Hz-wide Gaussian-noise target had the following center frequencies: 375, 1125, 1875 and 3375 Hz with the 1125-Hz masker (see Fig. 18a) and 5625, 6375, 7125 and 8625 Hz with the 6375-Hz masker (see Fig. 18b).

The modeling results of the 1125-Hz masker show an increase in masked thresholds with increasing masker bandwidth. There is a maximum difference of about 22 dB for the on-frequency situation if the sinusoid and the 750-Hz-wide noise masker are compared. The 1125-Hz experimental results show a difference in threshold between the sinusoid and the 750-Hz-wide noise masker of about 50 dB. The corresponding values for the 6375-Hz masker are about 10 dB for the model and about 20 dB for the subjects.
About 65 dB is the highest threshold value reached for the experimental results and that is for both the on-frequency situations. For the modeling results these values are respectively 61 and 69 dB for the 1125-Hz and the 6375-Hz masker.
The model predicts that the highest thresholds for all the maskers are at the on-frequency situation. The experimental results confirmed this except for the 1125-Hz sinusoidal masker, because there the peak can be found at 1875 Hz instead of 1125 Hz.

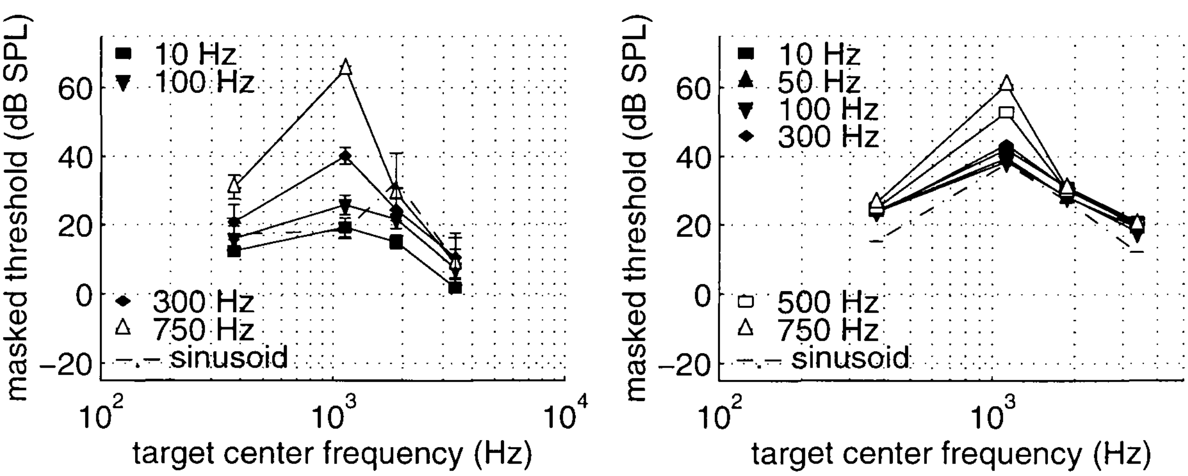

Fig. 18a: The left panel shows the experimental results and the right panel the modeling results of masked thresholds of a Gaussian-noise masker with a center frequency of 1125 Hz and a level of 70 dB SPL. The noise masker had a variable bandwidth of 10 (black squares), 50 (upward triangles), 100 (downward triangles), 300 (diamonds), 500 (white squares) and 750 Hz (white upward triangles). Also thresholds of a single sinusoidal masker are shown (dashed-dotted line). A 750-Hz-wide Gaussian-noise target was used with center frequencies of 375, 1125, 1875 and 3375 Hz (the experimental results are a copy of Fig. 11a).

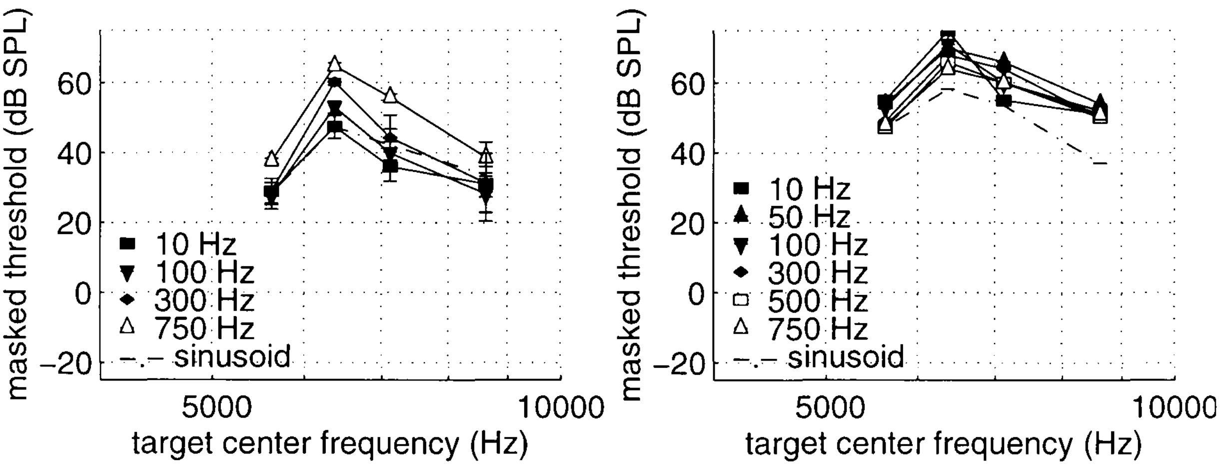

Fig. 18b: Same format as in Fig. 18a, only the center frequency of the masker was 6375 Hz and the center frequencies of the target were 5625, 6375, 7125 and 8625 Hz (the experimental results are a copy of Fig. 11b).

Discussion

Experiment 1

The critical bandwidth of auditory filters increases with increasing center frequency. If the bandwidth of the noise target is kept constant, like in all experiments done for this report, and the critical bandwidths increase then the relative size of the target decreases. This results in increasing masked thresholds for increasing center frequencies, because the target and masker are more likely to fall within one auditory filter. It is expected that at the high frequencies the off-frequency filters are used less.

With an increase in masker level the masked threshold increases as well. Egan and Hake (1950) found for an on-frequency situation an increase in masked threshold of 18 or 19 dB for a noise masker of 410 Hz that had been increased in level by 20 dB. The experimental results in this report show differences ranging from about 8 dB for a 1125 Hz center frequency to 18 dB for a 8625 Hz center frequency. So these differences in masked thresholds for the 1125 Hz condition are smaller than those found by Egan and Hake, the others are comparable. But Egan and Hake used a tonal target while for this report a noise target was used. Jendro (1992) determined masking patterns for noise as well as for tonal maskers, using a noise target with a bandwidth of one Bark (see Fig. 19). He found that on-frequency the growth in masking was linear, while it was less than linear for the low-frequency side of the masking pattern and more than linear for the high-frequency side. Jendro found increases in masked thresholds of 18 to 20 dB for a 20-dB increase in masker level for a tonal masker and of 15 to 21 dB for a 20-dB increase for a noise masker. All these results are comparable to those of Egan and Hake.

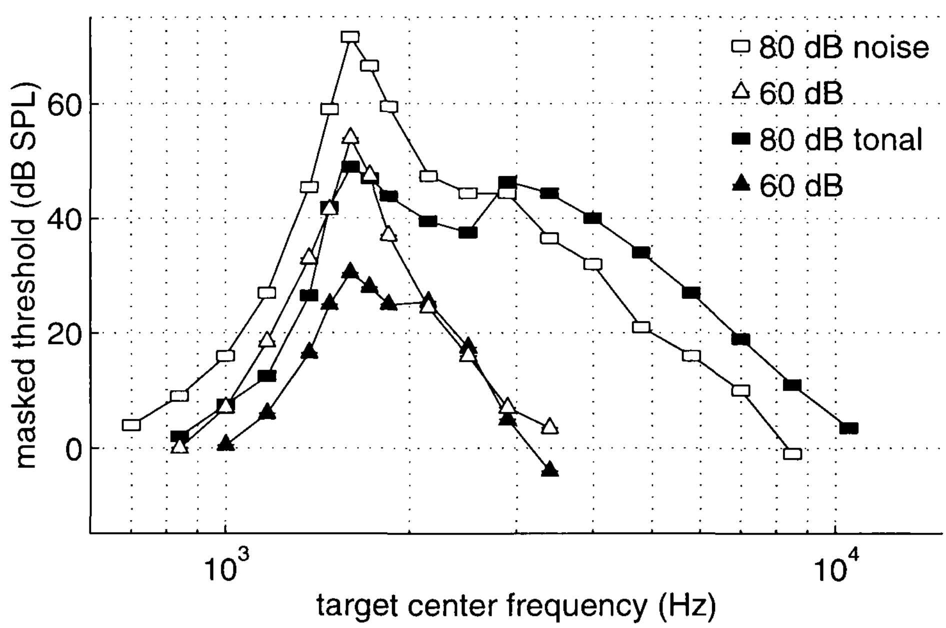

Fig. 19: Masking patterns determined with a noise (black symbols) and a tonal masker (white symbols) of which the level varied between 60 (upward triangles) and 80 dB SPL (squares). The target and noise masker both consisted of a one-Bark-wide noise. The center frequency of the masker was 1600 Hz and that of the target varied. The data are replotted from Jendro (1992).

A possible explanation for the smaller differences in masked threshold for the 1125-Hz situation in comparison to the higher center frequencies can be that the masking pattern of a tonal masker shows a less-than-linear growth for the low-frequency side of the masking pattern and a linear growth for the on-frequency situation (Egan and Hake, 1950, Jendro, 1992). Due to the asymmetry of the masking pattern, it is very likely that detection of the noise targets occurs at the low-frequency side of the masking pattern. Since in the present experiments the target is always 750-Hz wide independent of the center frequency, the lower edge of the target will be further away from the target center frequency for low frequencies then for targets with a bandwidth of one Bark, like used by Jendro, and vice versa for higher center frequencies. Because a 750-Hz bandwidth is comparable to one Bark for a center frequency of about 4100 Hz, the situation will be different at the highest masker frequency of 8625 Hz. This results in a change in the place of detection. For the 1125-Hz condition the detection would then take place at a lower frequency compared to other conditions. And at these lower frequencies is the growth in masking smaller so the difference in masked thresholds are then also smaller than for higher center frequencies of masker and target. One reason why Jendro did not find this less-than-linear growth can be that he used noise targets with a bandwidth of one Bark. A second reason can be that for his noise target and noise maskers the bandwidths were the same, so he was in fact measuring just noticeable differences in intensity. That is why he found about the same masked thresholds for different center frequencies, see Fig. 20. In the experiments done for this report the relative size of the target decreased with increasing center frequency.

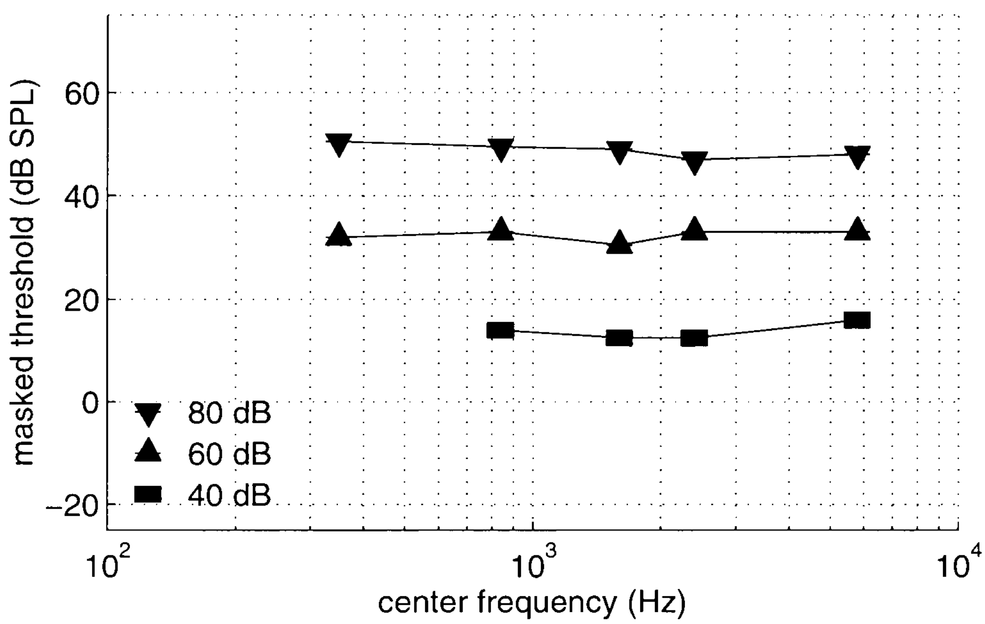

Fig. 20: Masked thresholds for a sinusoidal masker and a one-Bark-wide noise target. The level of the masker was 40 (squares), 60 (upward triangles) or 80 dB SPL(downward triangles) and the center frequencies were 350, 840, 1600, 2400 and 5800 Hz. (The 350-Hz 40-dB value was below absolute threshold.) The data are replotted from Jendro (1992).

In Fig. 21 results from Jendro's study (black symbols) and from the present study (white symbols) for a tonal masker and a noise target are compared. Jendro used a one-Bark-wide noise and the author used a 750-Hz-wide noise. But for a center frequency of about 4000 Hz one Bark is 700 Hz, so that is why the center frequency of 4125 Hz is chosen to be compared to the frequency-invariant results from Jendro. The results indicate that masked thresholds increase 18 dB for a 20-dB-increase of the masker, in both studies, which is a bit less than linear. The absolute difference of about 5 dB between the two studies is probably caused by experimental differences.

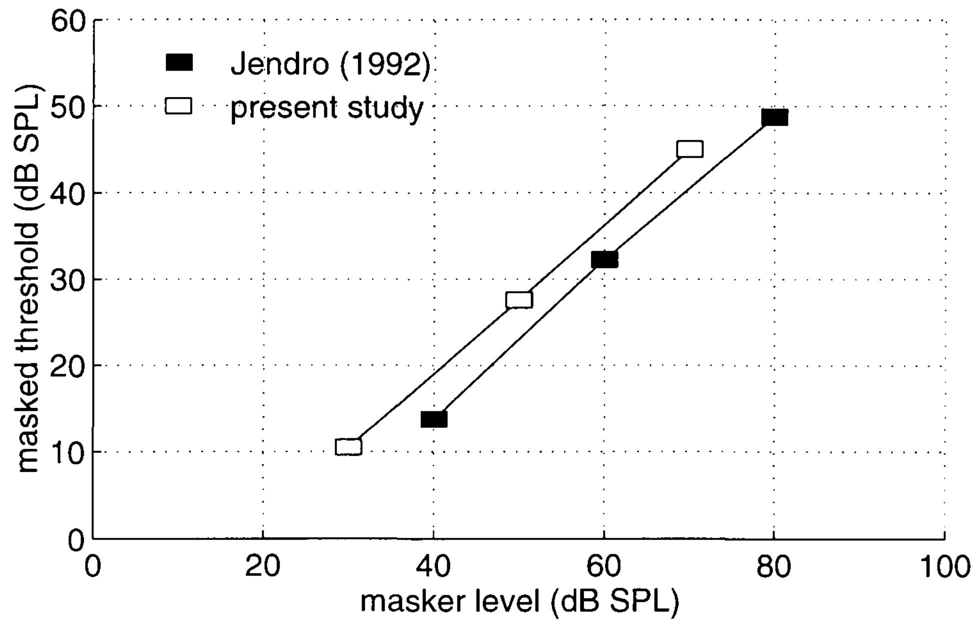

Fig. 21: Masked thresholds from Jendro (black symbols) and from the present study (white symbols) for a tonal masker and a noise target with a variable level. The center frequency used by the author was 4125 Hz for both target and masker, and the levels were 30, 50 and 70 dB SPL The results of Jendro had levels of 40, 60 and 80 dB SPL.

If the masked thresholds of experiment 1 for the experimental and the modeling results are compared then it shows that the masked thresholds of the model are about 3 to 20 dB higher than for the experimental results. The modeling results increase more linearly with level than the experimental results. A reason for this might be that for the model a gammatone filterbank is used. These filters stay the same with level and therefore, a more linear growth in masking is expected as well for low as for high frequencies.

Experiment 2

For increasing center frequencies the masked thresholds increase as well, for an explanation, see experiment 1.

As can be seen in Fig. 7a, b and c, the thresholds for the single sinusoid are comparable with the lowest thresholds for three sinusoids. But with an increase in sideband level the thresholds increase also, only the -23 and -33-dB relative sideband levels are an exception, because they are comparable to the threshold of the single sinusoid with an overall level of 70 dB SPL.
The differences in masked thresholds between lowest and highest sideband levels in experiment 2a range from 5 to 15 dB, with smaller differences at higher center frequencies. It was thought that the more the sinusoidal masker was modulated, the lower the masked thresholds would be (see Nelson and Schroder, 1996). But the 'listening-in-the-valleys' hypothesis does not seem to hold here.

The thresholds of experiment 1 are comparable to the -23 and -33-dB relative sideband levels of experiment 2a, because the levels are the same and the differences in modulation are not audible. To study the influence of modulation depth on masked thresholds a comparison is made between the 74.8-dB condition of experiment 2a (the 0-dB relative sideband level in Fig. 7a) and the weighted average of the following three conditions, all with an overall level of 70 dB: The single sinusoid from experiment 1, and the data for the relative sideband levels of -23 dB and -33 dB from experiment 2a. If these two conditions are compared, then a difference in masked thresholds of about 9 to 14 dB is found (see Table 2). About 5 dB can be explained, due to the overall difference in level. But also an effect of the spectral change can be calculated. The masker of experiment 2a consists of 3 sinusoids, has a bandwidth of 100 Hz and masks more than the single sinusoid of experiment 1. This difference in masking can be calculated with the estimate for the slope of the sinusoidal masking pattern for the low-frequency side of 27 dB/Bark (Zwicker and Fastl, 1990). The results can be found in Table 2. If the differences in level and masking is accounted for than the unexplained differences range from about 1 to 5 dB (see column 5 in Table 2). It is obvious that these increases in threshold can not solely be explained by spectral masking, but that other, probably temporal, effects are involved.

CF (Hz)	Diff. in thresholds (dB)	Diff. in level (dB)	Spectral diff. (dB)	Un-explained (dB)
1125	13.8	4.8	7.1	1.9
4125	10.3	4.8	1.9	3.6
6375	11.1	4.8	1.1	5.2
8625	9.7	4.8	0.8	4.1

Table 2: The differences in masked thresholds are analyzed for the averages of the three 70-dB thresholds (from experiment 1 and the -23 and -33-dB relative levels from experiment 2a) and the 74.8 dB, 0-dB relative levels of experiment 2a. In column two the threshold differences between these two conditions are shown, in column three the differences in masker level and in column four the calculated spectral effect are given. In column five the possible influence of temporal effects is shown, which is the differences between column two and columns three and four.

If the experimental and modeling results of experiment 2a are compared, then a big difference in masked thresholds can be seen with increasing sideband levels. The modeling results hardly predict any increase in thresholds, a maximum of 8 dB for the -33-dB relative level in comparison to the 0-dB relative level, while the experimental results show a maximum increase of about 20 dB. The difference in level between those relative sideband levels is 4.8 dB. So the model obviously does not predict that envelope fluctations have a big influence on the masked thresholds. Thus the same conclusion can be taken as for the experimental results and that is that the 'listening-in-the-valleys' hypothesis does not seem to hold for these results. Nevertheless do the differences between the thresholds for the different sideband levels increase with an increasing level of the center component, just like the effect in the experimental results.

Buus (1985) found that envelope fluctuations in a masker may result in release from masking in an off-frequency situation, where the target has higher frequencies than the masker. His results show that a two-tone complex masks less than a single tone with the same overall level. This is in contrast with the results found in this report for three sinusoids, because the complexes with the sinusoids 10 or 50 Hz separated from the center component mask more than a sinusoid with a flat spectrum (see experiment 1) and the same overall level. But this difference might be caused by the on- versus off-frequency situation, and the use of noise targets by the author, while Buus used tonal targets.

For sidebands 10 Hz separated from the center component (pilot experiments, see Fig. 8a, b and c) the modulation of the envelope is slower than for sidebands 50 Hz separated from the center component (experiment 2a, see Fig. 7a, b and c). Therefore it was expected that the masked thresholds were lower for the 10-Hz variant because in the slowly varying valleys it should be easier to detect the masker than in the faster varying envelope of the 50-Hz separated sidebands.
If the results of experiment 1 and the pilot experiments (see Fig. 8a, b and c) are compared than very similar thresholds are found. This is different from what was expected because the

masked thresholds for the three-tone complex with a -23 and a -33 dB relative sideband level were expected to be lower than for the single sinusoid that had the same overall level. But all the thresholds are similar, this while the pilots had a level ranging from 70.0 dB to 73.0 dB versus 70.0 dB for the single sinusoid. The effect of the envelope modulation of the three-tone complexes can be compensated by the differences in level, but this only accounts for the -3-dB and the -13-dB relative sideband levels. No further explanation is known for the similarity in threshold.

The masked thresholds in Fig. 9 of experiment 2b, the multiplied-noise experiment, are all lower than the results of experiment 2a. For high frequencies the differences are small, ranging from 0.7 dB to 5.1 dB. But for the 1125-Hz condition the differences range from 0.6 dB to 7.6 dB. This could be caused by a spectral difference between the multiplied-noise masker versus the three-tone complex. Since the overall level of these two maskers is the same, the level of each sinusoidal component is higher than the spectral level of the noise masker at that frequency. This might change the spectral pattern, and thus the masked thresholds in favor of the noise masker. These differences also indicate that periodic modulation (of the three sinusoids of experiment 2a) does not lower the masked thresholds as much as the aperiodic modulation with deep valleys of a multiplied-noise masker.
The thresholds of experiment 1 for the single sinusoid are comparable to those of the multiplied-noise experiment if the difference in overall level is accounted for, only the 1125-Hz conditions have lower thresholds for the tonal masker. Thus an aperiodic modulation of a 100-Hz-wide multiplied-noise masker (like in experiment 2b) does not make a difference in thresholds when compared to an unmodulated tonal masker. Van der Heijden (1995) found a release of masking for a 100-Hz-wide multiplied-noise masker in comparison to a tonal masker. The masked thresholds were about 10 dB lower for the multiplied-noise masker than for the tonal masker at a masker level of 70-dB. This was an off-frequency situation with the target above the masker in frequency and a tonal instead of a noise target.

A part of the results of experiment 2b, experimental results with a multiplied-noise masker of 74.8 dB, were about the same as the same experiment done with a Gaussian-noise masker of 74.8 dB SPL (see Table 1). The differences between a multiplied-noise and a Gaussian-noise masker ranged from 0.1 to 3.5 dB higher thresholds for the multiplied noise with smaller differences at high center frequencies. A multiplied noise has more and deeper valleys than a Gaussian noise, but this seems to have little influence on the thresholds.
The modeling results showed higher thresholds for the multiplied noise as well with differences ranging from a 0.3-dB to a 5.8-dB, again with smaller differences at high center frequencies.
Previous experiments comparing multiplied and Gaussian-noise maskers were done by van der Heijden (1995). He found for an off-frequency situation, with center frequencies of 1300 Hz for the masker and 2000 Hz for the tonal target, a difference in masked thresholds for Gaussian-noise versus multiplied-noise maskers. The thresholds were about 8 dB higher for a 80-dB Gaussian-noise masker but this difference decreased towards 0 dB for a 60-dB masker. For a level of 72 dB SPL (comparable with the level used for the experiments described here) the threshold was about 4 dB higher for the Gaussian-noise masker than for the multiplied-noise masker. Two reasons could be causing the differences between the results of van der Heijden and the results of the experiments done by the author. The first is that van der Heijden used tonal targets and I used noise targets and the second reason could be that I measured on-frequency and van der Heijden off-frequency.

Experiment 3

An explanation for the differences in masked thresholds between the tonal and the noise maskers of experiment 3 (they range from 1.5 at high and 8.5 dB at low frequencies) might be that they are caused by a difference in spectral resolution of the auditory filters. Toward low frequencies the filters have a smaller critical bandwidth, and it is thus possible that a noise masker excitates more filters than a sinusoid. Thus the level of the target needs to be higher for a noise masker before it can be detected. This is also the case for higher frequencies but the noise masker excitates fewer filters in comparison to the tonal masker because of the increase in critical bandwidth.

The only elaborate reference known to the author for simultaneous masking experiments with noise targets is from Jendro (1992). He used tonal and noise maskers, five different center frequencies and three masker levels. And for this on- and off-frequency experiment noise maskers and targets were used with a bandwidth of one Bark.
For the on-frequency situation, Jendro found 20-dB-higher masked thresholds for a narrow-band noise masker in comparison to a tonal masker. In experiment 3, where also a narrow-band noise masker or a tonal masker and a noise target were used, smaller differences of 8.5 to 1.5 dB were found. An explanation might be that Jendro used a noise target and masker each of only one Bark wide, while for this report a 750-Hz-wide noise target and a 100-Hz-wide masker were used. Jendro found for the noise masker a frequency-invariant threshold of about 70 dB for a 80-dB masker (like the 50-dB thresholds for a 80-dB tonal masker, see Fig. 18 or 20), because the bandwidth of the noise masker compared to the noise target was kept identical. In this way he was measuring just noticeable differences in intensity instead of spectral masking. In this report masked thresholds for a noise masker and a noise target were found that decreased with decreasing center frequencies, ranging from about 50 to 30 dB for a 70-dB masker. But the relative size of masker and target decreased with decreasing center frequency.

From the results of experiment 3 it follows that the differences in masked thresholds between a 100-Hz-wide noise versus a tonal masker for a noise target vary between 1.5 and 8.5 dB. So the assumption that this difference is 9 dB, which is made for use in coding, is not right for all situations.

In the modeling results of experiment 3 the masked thresholds are slightly higher for the tonal masker than for the noise masker, while the opposite is observed for the experimental results. A possible reason for these modeling results is the gammatone filterbank in the model. These filters are deduced from experiments done with noise maskers, and therefore, thresholds for the noise masker are relatively better predicted than those of the tonal masker.

Experiment 4

The discussion of experiment 4 is split up into two parts, namely the on-frequency situation, where the target and masker have the same center frequency, and the off-frequency situation, where the target and masker have different center frequencies.

On-frequency situation

Figures 11a and b show that for different types of maskers the masked thresholds vary. For instance an increase in bandwidth results in an increase in masked thresholds. These differences can range from 0 up to 50 dB for a tonal masker compared with a Gaussian-noise masker with increasing bandwidth. There is also an influence caused by the target's center frequency, because the differences are smaller for higher frequencies.
For an increase in masker bandwidth in experiment 4a the masked thresholds also increase. With an increase in masker bandwidth the masking pattern widens. Since the masker bandwidth is smaller than the target bandwidth the widening of the masking pattern leads to an in-

crease in masked thresholds. For the 750-Hz-wide masker the target and masker bandwidths are equal, so that there are no spectral differences between masker and target and detection is based on overall intensity differences.
The increase in thresholds might also be caused by cubic distortion products of the masking noise band (cf. van der Heijden, 1995). For an example we look at the low-frequency side of the masking pattern, where detection is assumed to take place. For a noise masker of 100-Hz width a cubic distortion band is found stretching 100 Hz below the low-frequency side of the masker, while for a 750-Hz wide masker this cubic distortion band stretches over a range of 750 Hz. Thus with an increase in bandwidth the masking pattern changes and masks more towards lower frequencies and this might cause an additional increase in the masked thresholds. Maybe there is also an antagonistic effect, because the overall power of the maskers is kept constant, but for a 750-Hz wide masker there is less power per Hz than for a 10-Hz wide masker. So this might result in a release from masking for an increase in bandwidth.

The masked thresholds for a 750-Hz-wide noise masker and a 750-Hz noise target are about 65 dB for the 1125-Hz and for the 6375-Hz masker center frequency. This indicates the just noticeable difference in intensity, because a masker of 70 dB plus a target of 65 dB results in a stimulus of 71,2 dB and that is just discriminable from a 70-dB stimulus. The model obviously does not predict intensity difference detection, because there the masked thresholds are 61 and 69 dB SPL for the 1125-Hz and the 6375-Hz masker.

One remark on the work of Jendro (1992) is that he found low masked thresholds in comparison to the results in this report. For an 80-dB masker level and a noise target Jendro found thresholds of 70 dB SPL, while the author of this report found 65-dB thresholds for a 70-dB masker (both masker and target had a bandwidth of 750 Hz).

Off-frequency situation

For the off-frequency situation also an increase in threshold can be found for an increase in bandwidth, for a discussion of the possible reasons, see Discussion: On-frequency situation. But this effect is smaller for the off-frequency situation than for the on-frequency situation, particularly for the 1125-Hz masker (see Fig. 11a and b). A reason might be that for the 750-Hz-wide masker in the on-frequency situation thresholds are particularly high because detection is based on an intensity-discrimination cue. In the off-frequency situation, also for this masker, thresholds are determined by spectral masking, and therefore the influence of masker bandwidth is more gradual.

The asymmetry of masking can be judged by comparing off-frequency thresholds for the targets one subband below or above the masker. Since spectral masking is generally asymmetric with more masking towards high frequencies (see Fig. 2), the same asymmetry is expected for the present data. And indeed such an asymmetry is seen for the 6375-Hz masker (see Fig. 11b). For the 1125-Hz masker (see Fig. 11a), however, the thresholds for the target below the masker are approximately as high as those for the target one subband above the masker. This effect is probably a consequence of the higher absolute thresholds for the lowest target center frequency.

The asymmetry in masked thresholds is stronger for the sinusoidal masker than for the Gaussian-noise masker. A possible reason could be that a noise masker masks relatively more toward lower frequencies because of distortion products.

The masked thresholds for the 375-Hz condition are higher than the thresholds for the 3375-Hz condition of the experimental results with the 1125-Hz masker. It is expected that the masked thresholds at the low- and at the high-frequency side of the masking pattern reach the same threshold values again (see also Fig. 2). The reason that this does not happen might be the influence of the absolute threshold at the low-frequency side of the masking pattern (for one subject data of experiment 4a are plotted in Fig 11a together with the subject's absolute threshold). Also for the 6375-Hz masker center frequency the absolute threshold can account for higher thresholds at the low-frequency side, in this case for the 5625-Hz versus the 8625-Hz values.

In Figure 11a a peak-shift effect can be seen for a tonal masker and a Gaussian-noise target. The masked thresholds for the sinusoid are not the highest for the on-frequency situation, this in contrast to the masked thresholds of all other maskers, but for higher target center frequencies, namely from 1325 to 1625 Hz (see Fig. 12a). The masker than overlaps spectrally with the low-frequency side of the target. This occurs only for the maskers with the 1125-Hz center frequency and not for the 6375-Hz one. A possible reason for this peak-shift might be the difference in masking patterns for a sinuoidal versus a noise masker. In Fig. 19 an example of a masking pattern is shown of a noise and a tonal masker measured by Jendro (1992). An interpolation of these results indicates that a 70-dB sinusoidal masker masks more toward higher center frequencies than a 70-dB noise masker. The results in this report confirm that.
In the masking pattern of the sinusoid (Fig. 19) two 'bumps' are seen, that means: the highest thresholds can be found for the on-frequency situation and for higher center frequencies. It could be the case that this 'second bump' causes the peak-shift for the 1125-Hz center frequency. Jendro found these 'bumps' for almost all used center frequencies for a sinusoidal masker, except for the 350-Hz condition (he did not find this for a noise masker). A reason why no peak-shift was found for the 6375-Hz center frequency could be that not enough thresholds were measured for different target center frequencies, because the results of Fig. 12a show that this peak can be very slender.

In Fig. 13a and b it can be seen that the thresholds for the tonal masker are generally lower than for the noise masker except for the lowest masker center frequency. This can be explained by looking at the differences in masking patterns of these two types of maskers. A noise masker masks more on-frequency and masks more towards lower frequencies than a tonal masker, maybe because of distortion products, so that is why the thresholds are higher for the higher center frequencies for the noise masker. At the lowest masker center frequency the thresholds are higher for the tonal masker because the sinusoid masks more towards higher frequencies than the noise masker.

Conclusions

The following conclusions can be derived for noise targets of 750-Hz width:

Aperiodic and periodic modulation of a masker give the same masked thresholds in an on-frequency situation.

The masking pattern of a tonal masker is more asymmetric than for a noise masker, possibly due to distortion products induced by the noise masker.

Differences in masked thresholds for an on-frequency situation for a tonal versus a noise masker with a 750-Hz-wide noise target can range from 0 up to 50 dB, going from low to high threshold values with increasing masker bandwidth.

The assumption made in coding applications that a noise masker masks more than a tonal masker, is only correct for on-frequency targets and for targets below the masker. At the high-frequency side of the masking pattern, a tonal masker often leads to higher thresholds than a noise masker of the same level.

The assumptions made concerning masking behaviour of tonal versus noise maskers for coding algorithms should be checked by means of more psychoacoustical research.

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References

Brandenburg, K. and Stoll, G., 1994. ISO-MPEG-1 Audio: A generic standard for coding of high-quality digital audio. *J. Audio Eng. Soc.* 42 (10), 780-792.

Breebaart, J., Par, S. van de and Kohlrausch, A., 1998. Binaural signal detection with phase-shifted and time-delayed noise maskers. *J. Acoust. Soc. Am.* 103 (4), 2079-2083.

Buus, S., 1985. Release from masking caused by envelope fluctuations. *J. Acoust. Soc. Am.* 78 (6), 1958-1965.

Buus, S., 1990. Level discrimination of frozen and random noise. *J. Acoust. Soc. Am.* 87 (6), 2643-2654.

Dau, T., Püschel, D. and Kohlrausch, A., 1996a. A quantitative model of the "effective" signal processing in the auditory system. I. Model structure. *J. Acoust. Soc. Am.* 99 (6), 3615-3622.

Dau, T., Püschel, D. and Kohlrausch, A., 1996b. A quantitative model of the "effective" signal processing in the auditory system. II. Simulations and measurements. *J. Acoust. Soc. Am.* 99 (6), 3623-3631.

Egan, J.P. and Hake, H.W., 1950. On the masking pattern of a simple auditory stimulus. *J. Acoust. Soc. Am.* 22 (5), 622-630.

Hawkins, J.E. and Stevens, S.S., 1950. The masking of pure tones and of speech by white noise. *J. Acoust. Soc. Am.* 22, 6-13.

Heijden, M.L. van der, 1995. *A comparison of masking by tones and noise.* Ph. D. thesis, Technical University of Eindhoven.

Jendro, A. 1992. *Durchführung und Auswertung eines Hörtests bezüglich der Verdeckungseffekte des menschlichen Gehörsinns im Frequenzbereich.* Master thesis, University of Duisburg.

Johnston, J.D. 1988. Transform coding of audio signals using perceptual noise criteria. *IEEE J. Selected Areas in Commun.* 6, 314-323.

Johnson-Davies. D.B. 1981. *The analogy between psychophysical and physiological tuning curves in hearing.* Ph. D. thesis, Cambridge University.

Levitt, H. 1971. Transformed up-down procedures in psychoacoustics. *J. Acoust. Soc. Am.* 49, 467-477.

Nelson, D.A. and Schroder, A.C. 1996. Release from upward spread of masking in regions of high-frequency hearing loss. *J. Acoust. Soc. Am.* 100 (4), 2266-2277.

Patterson, R.D., Allerhand, M.H. and Giguère, C. 1995. Time-domain modeling of peripheral auditory processing: A modular architecture and a software platform. *J. Acoust. Soc. Am.* 98 (4), 1890-1894.

Veldhuis, R. and Kohlrausch, A., 1995. Waveform coding and auditory masking. In: *Speech coding and synthesis*, eds Kleijn, W.B. and Paliwal, K.K., Elsevier Amsterdam, 397-431.

Verhey, J. and Dau, T., 1996. Simulations of spectral masking with a model incorporating an optimal decision strategy. In: *Psychoacoustics, speech and hearing aids*, ed Kollmeier, B., World Scientific Singapore, 29-34.

Zwicker, E. and Fastl, H. 1990. *Psychoacoustics: Facts and models.* Springer-Verlag, Berlin.

Appendix

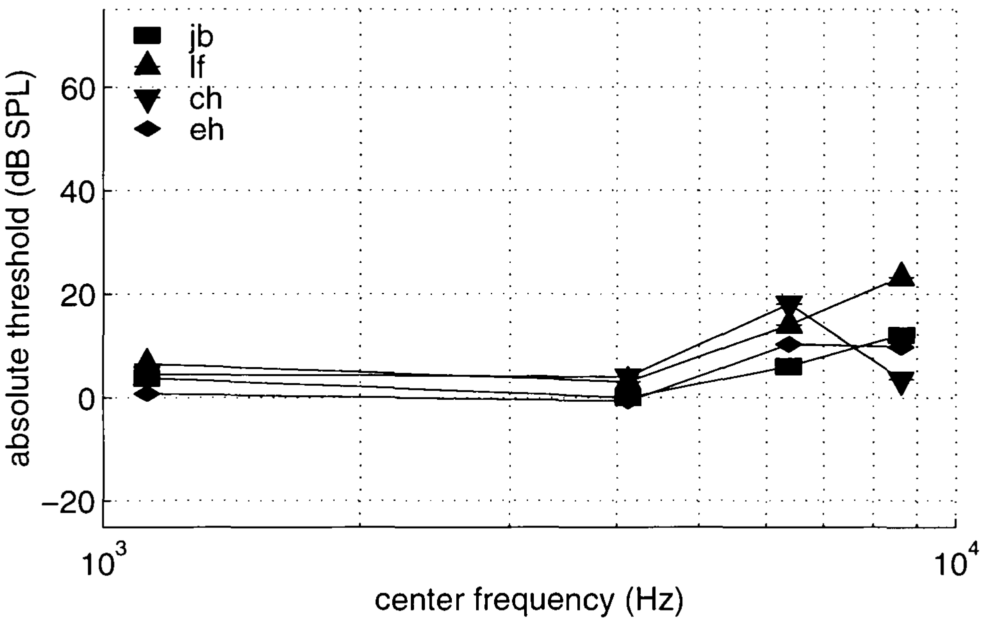

Fig. 1: Absolute thresholds measured for four subjects, jb (squares), lf (upward triangles), ch (downward triangles) and eh (diamonds). Four different center frequencies were used, 1125, 4125, 6375 and 8625 Hz.