Across-channel processing of amplitude modulation

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ABSTRACT

In typical modulation detection experiments, a sinusoidal signal modulation is applied to broadband noise as the carrier. In such conditions, the carrier's envelope at the outputs of different peripheral auditory channels can be considered as being almost uncorrelated while the signal modulation is coherent across auditory channels. Models of auditory processing often combine the information about the signal modulation optimally in terms of signal detection theory, assuming independent "observations" in different auditory channels. However, various experiments demonstrate that modulations imposed on spectrally separated carriers can interfere, indicating that (prior to the decision stage) amplitude modulation appears to be processed not independently across frequency. The present study examines sinusoidal amplitude modulation (SAM) detection on multiple carriers and as a function of carrier bandwidth. In addition, modulation detection interference (MDI) with variable carrier bandwidth is explored. Simulations obtained with the envelope power spectrum model (EPSM) (Ewert and Dau, 2000) are presented and compared to the data. Strategies of across-frequency combination of the envelope information extracted in different peripheral channels are discussed.

METHOD

Modulation detection thresholds were obtained using an adaptive three-interval forced-choice (3IFC) procedure (2-down 1-up rule). All signals were 500 ms long including 50 ms cos^2 ramps. The stimuli were presented diotically via headphones (Sennheiser HDA 200) in a sound-attenuating booth. The headphones were digitally equalized to match a flat frequency response in the range from 100 to 20000 Hz. The signal level of each presented carrier was 65 dB SPL. For each subject, the final modulation detection threshold was taken as the average across three threshold estimates.

MODELS

Model 1

The EPSM was used to predict modulation detection thresholds. The model incorporates a gammatone filterbank to account for effects of peripheral filtering. In each peripheral channel (or critical band) the integrated envelope power at the output of a modulation filter tuned to the signal modulation was calculated. Observations were combined across audio-frequency channels by assuming that $d' = (\sum_{i=1}^{n}(d'_i)^2)^{1/2} = (\sum_{i=1}^{n} 2S_i/N_i)^{1/2}$, where d'_i denotes the sensitivity index for peripheral channel i, which is proportional to the square root of the signal-to-noise ratio S_i/N_i in this channel, and d' denotes the overall sensitivity index. This is equivalent to a linear combination of independent observations. To relate the combined information to thresholds, a -6 dB S/N-criterion corresponding to a 1 dB $(S+N)/N$-criterion was assumed.

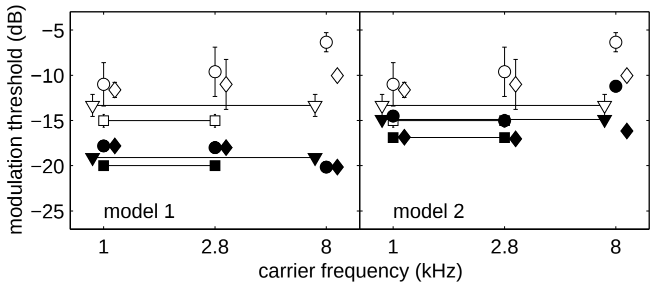

FIG. 1. Predicted 8-Hz SAM thresholds (closed symbols) and average data (open symbols) for different combinations of modulated narrowband-noise carriers and interfering narrowband-noise bands. All bands had the same bandwidth of 200 Hz. The upper edge frequency is indicated at the bottom. The diamonds represent modulation thresholds for a single carrier band presented without any interfering bands. In all other conditions, three bands with upper edge frequencies of 1, 2.8 and 8 kHz were presented simultaneously. Modulations were applied to only one of the bands (circles), to the two lower bands (squares, 1 and 2.8 kHz upper edge frequency), or to the two bands at 1 and 8 kHz (triangles).

Model 2

The second version of the model incorporates an across-channel process. Some amount of non-signal envelope excitation is fed back to each peripheral channel. This amount equals the quarter of the sum of the integrated envelope noise power across all peripheral channel. The fraction of 1/4 was chosen to match the empirical results.

I MULTIPLE NOISE CARRIERS

8-Hz SAM thresholds for different combinations of modulated narrowband-noise carriers and interfering noise bands were determined. The noise bands had a fixed bandwidth of 200 Hz, upper cutoff frequencies of 1, 2.8 and 8 kHz, respectively, and were statistically independent. First, modulation detection thresholds were determined for the three single noise carrier bands alone. Then, all three noise carriers were presented where the modulation was either imposed on only one of the carriers, or imposed simultaneously on the 1- and 2.8-kHz band, or on the 1- and 8-kHz band. Simultaneous modulations were always imposed in phase. Figure 1 shows the average experimental data (open symbols) and model predictions (filled symbols) for the both model versions described above.

Thresholds are slightly elevated when all three bands were presented and when the signal modulation was imposed on only one carrier (open circles) compared to the conditions, where only the single modulated bands were presented (open diamonds). About 2 to 5 dB performance gain is observed when two bands are modulated simultaneously (open squares and triangles). Generally, model 1

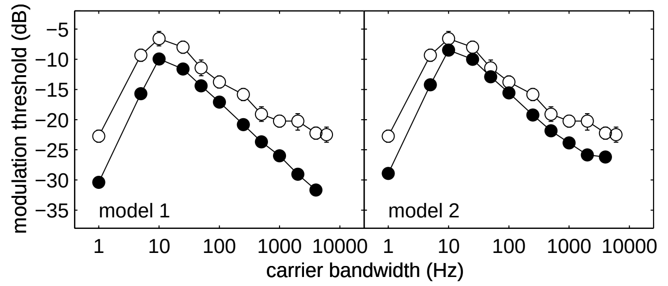

FIG. 2. Predicted modulation thresholds for a 5 Hz SAM as a function of the carrier bandwidth (closed symbols). The carrier bandwidth ranged from 1 to 4 kHz while the upper edge frequency of the carrier was fixed at 6 kHz. The open symbols are empirical data replotted from Dau *et al.* (1999).

can not account for any effects of across frequency interaction, since observations in different peripheral channels are assumed to be independent. Thus the detection performance can only gain from additional signal information in critical bands apart, but it can never suffer from noise in these bands. Hence, thresholds are the same for the single modulated bands (closed diamonds) and conditions where interfering bands were presented simultaneously (closed circles). When both the 1- and 2.8-kHz band are modulated, predicted thresholds are decreased by 2-3 dB (closed squares). Model 2 shows somewhat increased thresholds when interfering bands are presented and nearly the same performance gain as model 1 in case of two simultaneously modulated bands.

II EFFECTS OF CARRIER BANDWIDTH

Threshold predictions for a 5-Hz SAM as a function of the bandwidth of a Gaussian-noise carrier are presented. The bandwidth ranged from 1 (pure tone) to 4 kHz, while the upper cutoff frequency of the noise carrier was fixed at 6 kHz. Figure 2 shows the threshold predictions in comparison to experimental data (replotted from Dau *et al.* (1999)). The threshold curve shows a typical "bandpass"-like shape which is determined by the spectral distribution of envelope noise inherent in the carrier. Both model versions fit the threshold curve well. For a carrier bandwidth > 50 Hz, model 1 predicts constantly decreasing thresholds at a rate of 3 dB per doubling the carrier bandwidth. In contrast, model 2 better accounts for the lower slope observed in the data, although it asymptotes for the largest bandwidth.

III MODULATION DETECTION INTERFERENCE

Threshold predictions for a 5-Hz SAM imposed on a narrowband noise carrier centered at 1 kHz are presented. The bandwidth of the noise was varied in the range of 1 (pure tone) to 200 Hz, similar to experiment II. To examine effects of modulation detection interference (MDI), detection thresholds were obtained for a 5-Hz SAM applied to a sinusoidal carrier at 1 kHz in presence of an unmodulated narrowband noise centered at 4 kHz. Again the bandwidth of the noise was varied. Figure 3 shows predicted thresholds and average data from Dau (1999). Model 1 is able to account for the threshold curve when the signal modulation is applied on the narrowband noise (Fig. 2). However, it fails in the MDI condition. Model 2 also fits the MDI data reasonably well. Discrepancies are observed for small bandwidths of the interfering noise, where the predicted MDI effect is to low.

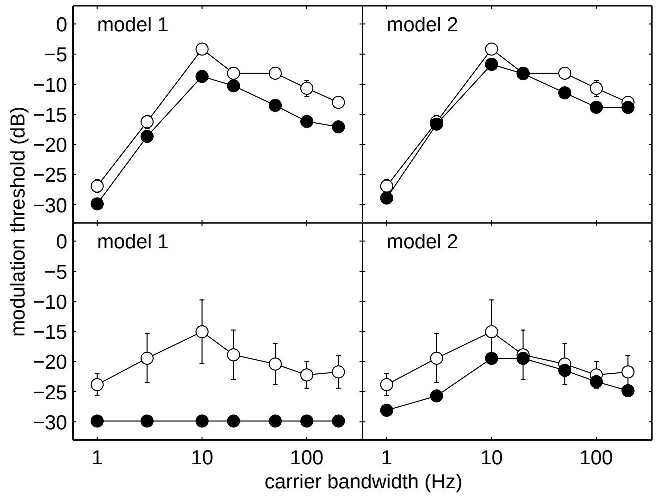

FIG. 3. The upper two panels show predicted modulation thresholds for a 5-Hz SAM as a function of the carrier bandwidth. The carrier noise band was centered at 1 kHz. The lower two panels show predicted modulation thresholds for a 5-Hz SAM applied to a 1 kHz tone in presence of an unmodulated noise centered at 4 kHz. Thresholds are plotted as a function of the bandwidth of the interfering noise. In addition, empirical data by Dau (1999) are shown (open symbols).

SUMMARY AND CONCLUSIONS

(1) For spectrally separated narrowband noise carriers, subjects are able to combine information about amplitude modulation optimally across frequency. Their performance in detecting an imposed SAM is improved by about 3 dB when two of three carriers are modulated instead of a single one, and when the modulation on each carrier alone is equally detectable.

(2) Thresholds for detecting an SAM on a single narrowband noise carrier are elevated when additional noise bands are presented several critical bands apart.

(3) For a large initial carrier bandwidth, each doubling of the carrier bandwidth leads to a decrease in threshold for an imposed SAM by about 2 dB. For a small carrier bandwidth (where only a few critical bands are involved) a 3 dB decrease in threshold per bandwidth doubling can be observed.

(4) Both, an optimal combination of signal (modulation) information across audio-frequency for narrowband carriers as well as effects of MDI obtained with an additional noise band located several critical bands apart from the modulated carrier, can be accounted for by model 2 presented here. This model adds internal noise, which is proportional to the amount of envelope noise in all excited peripheral channels, to each peripheral channel output.

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