Tone-in-noise detection: Observed discrepancies in spectral integration

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Abstract

Spectral integration for several tone-in-noise conditions is discussed and an experiment is conducted for both monaural (NoSo) and binaural conditions (NoSπ). Monaural detection thresholds for running-noise maskers increased for masker bandwidths up to the critical bandwidth and remained constant for larger bandwidths. Binaural conditions and monaural conditions with a frozen-noise masker revealed different spectral integration patterns that are monotonic for masker bandwidth below and beyond the critical bandwidth, an effect known as the apparently wider binaural critical band. Finally we show a different type of spectral integration obtained for binaural conditions with a reduced masker correlation (NρSπ) or for NoSπ with an overall interaural level difference. In these cases the integration patterns are non-monotonic with a maximum for masker bandwidths around the critical bandwidth.

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I. INTRODUCTION

In the context of tone-in-noise detection, spectral integration refers to the dependency of the detection thresholds on the bandwidth of the noise masker. In order to simplify the description we consider situations where the power spectral density (spectral level) of the masker is kept constant for all bandwidths.

Spectral integration was first formalized by the concept of the critical band proposed by Fletcher (1940). In this concept, thresholds for tones spectrally centered in a noise masker were increasing with increasing masker bandwidth up to a specific (the critical) bandwidth and remained constant for larger masker bandwidths. In subcritical situations the thresholds were increasing as the total energy of the masker. In supracritical situations thresholds remained constant because the filtering occurring on the basilar membrane removed all masker components outside the critical band. This view was later modified by Bos and de Boer (1966). They proposed a refinement for subcritical situations where it was found that besides energy principles that lead to integration rates of about 3 dB/octave, the external masker variability could also be the limiting factor for running-noise maskers resulting in integration rates of about 1.5 dB/octave. This approach was then extended to account for a phenomenon that was primarily observed for binaural conditions where the auditory filter appeared to be wider than that measured in monaural conditions (Sever and Small, 1979). In these conditions a monotonic increase of the thresholds is observed for bandwidths below and beyond the critical band. The phenomenon was explained by taking into account the contribution of information contained in off-frequency channels for conditions where the limiting factor for the detection process are the internal errors of the auditory system (van de

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Par and Kohlrausch, 1999; Breebaart *et al.*, 2000).

In addition to those known spectral integration patterns, we will present experimental data that reveal a third pattern. In this type of spectral integration, thresholds are increasing with increasing masker bandwidths for subcritical situations and are decreasing for further increases of the masker bandwidths. This type of non-monotonic spectral integration was observed in binaural conditions where the binaural stimuli were presented with an overall interaural level difference (ILD) and in conditions with a reduced interaural correlation of the noise masker.

II. EXPERIMENT

Spectral integration was measured for several conditions of tone-in-noise detection. The signal had a frequency of 500 Hz and the noise masker was centered on this frequency. It had a bandwidth between 10 and 1000 Hz and was presented as either a running or frozen noise. The experiment included monaural and binaural conditions. In addition to these common conditions we also included binaural conditions with an overall ILD of 30 dB and with a reduced interaural masker correlation.

A. Method and stimuli

A three-interval forced-choice procedure with adaptive signal-level adjustment was used to determine the thresholds. The three intervals of 300-ms duration were separated by pauses of 200 ms. A 200-ms sinusoid was added to the temporal center of one of the masker intervals. Feedback was provided to the subjects after each trial. The signal level was adjusted according to a two-down one-up rule tracking the 70.7% correct response level (Levitt, 1971). The initial step size for adjusting the level was 8 dB. After each second reversal of the level track, the step size was halved until a step size of 1 dB was reached. The run was then continued for another eight reversals. The median of the levels at these last eight reversals was calculated and used as a thresholds value. At least three threshold values were obtained and averaged for each parameter value and subject. Three subjects participated in this experiment, among them two of the authors. All subjects had normal hearing.

The noise masker was, unless stated otherwise, presented diotically (No) and the signal (500 Hz) was either presented diotically (So) or out-of-phase between the two ears (Sπ). The masker bandwidth was either 10, 20, 50, 100, 200, 500 or 1000 Hz. Bandwidths of 20, 50, 200 and 500 Hz were not measured for all conditions. For each masker bandwidth, the masker level was set to an overall sound pressure level of 65 dB. For running-noise conditions, the noise samples for each interval were obtained by randomly selecting 300-ms segments from a two-channel, 2000-ms bandpass-noise buffer. The 2000-ms noise buffer was created as a white Gaussian noise in the time domain that was filtered to the desired bandwidth in the frequency domain. For frozen-noise conditions, only one fixed 300-ms noise sample was used in all three intervals of an entire run. These bandlimited noise samples were generated in the same way as the noise buffers for random noise conditions followed by a normalization of their rms value. To exclude the possibility that the frozen-noise thresholds would depend on the specific waveform token, a different frozen-noise sample was used for each run. Not all conditions were measured with frozen-noise maskers. The partially interaurally correlated (ρ=0.93) noise maskers were generated by combining two independent noise samples. In order to avoid spectral splatter, the signals and the maskers were gated with Hanning windows that had 50-ms onset and offset ramps.

B. Results

The graphical pattern of spectral integration or its absence depends on the experimental conditions and how the detection thresholds are represented. The present experiment was conducted with noise maskers that had a constant overall power regardless of their bandwidth. Consequently, a variation of the masker bandwidth is in fact a redistribution of the energy of the noise masker in the frequency domain, which will therefore lead to variation in

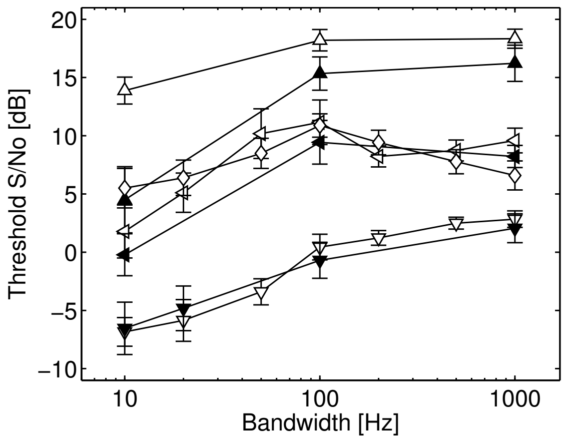

FIG. 1. Monaural and binaural masked thresholds expressed as signal to spectral density ratios are shown as a function of the masker bandwidth. Filled symbols represent thresholds obtained for frozen-noise maskers and open symbols represent thresholds obtained with running-noise maskers. Upward triangles represent NoSo thresholds. Downward triangles represent NoSπ thresholds. Left pointing triangles represent thresholds obtained for NoSπ conditions with an ILD of 30 dB. Diamonds represent NρSπ thresholds with an interaural masker correlation of 0.93.

the spectral density of the noise. In order to study solely the effect of spectral expansion of the masker and not its level variation, thresholds are represented in terms of signal to noise spectral density ratios, which will give the same integration pattern as a representation of the thresholds in dB SPL for an experiment conducted with a constant spectral level of the noise masker.

Average thresholds for three subjects are shown in Fig. 1 as a function of the masker bandwidth. Running-noise conditions are represented by the open symbols and frozen-noise conditions by the filled symbols. The error bars denote the standard deviation across the complete data set for each condition. For masker bandwidths smaller than 1 ERB, about 78 Hz at 500 Hz (Glasberg and Moore, 1990), thresholds in all conditions are increasing with increasing masker bandwidth. On the contrary, for masker bandwidths wider than 1 ERB three different behaviors are observed; detection at constant signal to noise spectral density ratio, thresholds still increasing with increasing masker bandwidths and an uncommon behavior of thresholds decreasing with increasing masker bandwidths.

Regarding the monaural conditions (upward triangles) we observe a thresholds change between masker bandwidths of 10 and 100 Hz of 1.3 dB/octave and 3.2 dB/octave for the running-noise (open symbols) and the frozen-noise masker (filled symbols) respectively. In the case of the frozen-noise masker the spectral integration corresponds to the variation of energy of the noise masker within the auditory filter, where a doubling of the bandwidth results in a 3 dB increase of the detection thresholds for bandwidths up to 1 ERB. In the case of the running-noise masker the integration rate is close to 1.5 dB/octave which fits with the assumption that detection is limited in this case by the variability of the noise masker on a per sample basis (Bos and de Boer, 1966). For masker bandwidths wider than 1 ERB, we observe no further spectral integration which is in line with the energy masking principles and the concept of the auditory filter. Some minor spectral integration can arguably be seen for the frozen-noise masker thresholds. This phenomenon has been previously reported (Breebaart *et al.*, 2000) and related to the apparently wider auditory filter known from binaural conditions (van de Par and Kohlrausch, 1999).

The phenomenon of an apparently wider critical band is particularly visible for binaural conditions (NoSπ, downward triangles) where one can clearly see that for both running- and frozen-noise maskers the increase in thresholds is monotonic below and beyond the auditory filter bandwidth. The thresholds for these binaural conditions are very similar for both types of noise masker. The spectral integration appears to be stronger for bandwidths smaller than 1 ERB, about 2.5 dB/octave, and weaker for bandwidths larger than 1 ERB and amounts to about 0.7 dB/octave. The subcritical value is in good agreement with the hypothesis that detection requires a constant change in the stimulus correlation. This happens at a constant signal-to-noise ratio and would ideally give a gain of 3 dB/octave. Such a behavior is expected if detection is not limited by external variability but internal noise in the auditory system. The monotonic increase of the thresholds beyond the critical bandwidth or in other words, the apparent wider critical bandwidth has been explained by assuming the contribution of off-frequency auditory filters to the detection for conditions in which detection is limited by internal errors (van de Par and Kohlrausch, 1999; Breebaart *et al.*, 2000). When the masker is narrower than 1 ERB the phenomenon is not particularly visible in the spectral integration pattern, but as the masker bandwidth slowly increases beyond 1 ERB, the information in the off-frequency auditory filters becomes gradually unusable (covered by the masker), resulting in minor spectral integration beyond 1 ERB. The phenomenon also occurs to some extent for monaural conditions with a frozen-noise masker but not with a running-noise masker. Effectively, as seen previously, in monaural conditions with running-noise the detection process is limited by the external variability of the masker waveform, while in conditions with frozen-noise the process is, similarly to binaural conditions (NoSπ), limited by internal limitations.

Detection thresholds for binaural conditions with additional overall ILD (left-pointing triangles) or a reduced masker correlation (open diamonds) lie between those obtained for monaural conditions (NoSo) and the binaural condition (NoSπ). Likewise they elicit spectral integration that also lies between patterns given by a detection process limited by external variability (increase of 1.5 dB/octave) and internal errors (increase of 3 dB/octave) for bandwidths smaller than 1 ERB. The thresholds obtained for the NoSπ condition with an overall ILD of 30 dB are clearly higher than those obtained for the plain NoSπ condition and are below the thresholds obtained for the monaural conditions. The thresholds are similar for both types of noise maskers. The integration rate is about 2.9 dB/octave. The spectral integration obtained for the NoSπ condition with a reduced masker correlation is about 1.7 dB/octave for masker bandwidths smaller than 1 ERB. In both cases an extension of the masker bandwidth beyond 1 ERB leads to a decrease in thresholds. Conditions with an overall ILD show a small decrease of about 1.6 dB for an increase of the bandwidth from 100 Hz to 1000 Hz. For the same bandwidths the decrease is about 4.3 dB for the thresholds obtained for the NoSπ condition with a reduced masker correlation.

A comparison of our data with other running-noise measurements adapted from the literature is shown in Fig. 2. Regarding the NoSπ conditions (downward triangles), our data

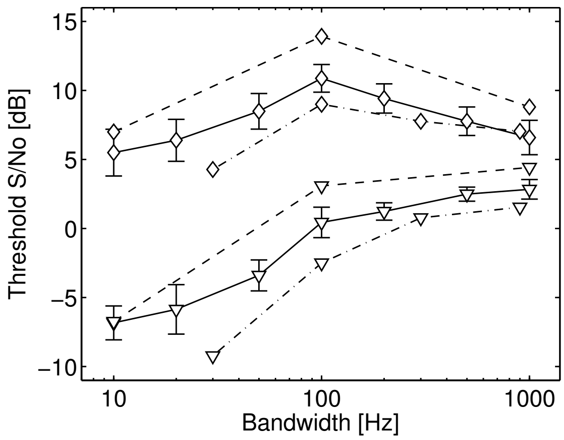

FIG. 2. Binaural masked thresholds expressed as signal to spectral density ratios are shown as a function of the masker bandwidth for running-noise maskers. Data are represented with the same convention of symbol types as in Fig. 1. The continuous lines show our data, the dashed lines represent data from Breebaart and Kohlrausch (2001); data adapted from van der Heijden and Trahiotis (1998) are shown as dot-dashed lines.

(continuous lines), the data from Breebaart and Kohlrausch (2001) (dashed lines) and the data from van der Heijden and Trahiotis (1998) (dot-dashed lines) all show a monotonic increase in thresholds, including masker bandwidths beyond 1 ERB. Regarding the NoSπ conditions with a reduced masker correlation (all diamonds) our data and those from Breebaart and Kohlrausch (2001) are obtained for similar experimental conditions and the same masker correlation of 0.93, those from van der Heijden and Trahiotis (1998) are taken from a data set as the best fit to our own data set which was found for a masker correlation of 0.87. For this condition, we also see a common behavior across the three data sets: thresholds are increasing with increasing masker bandwidth up to about 1 ERB and decrease for further extension of the bandwidth.

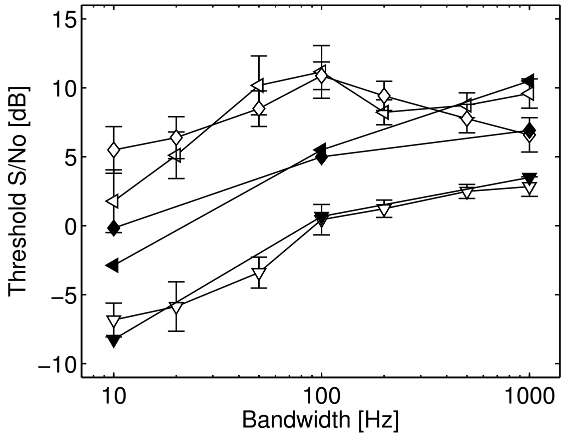

FIG. 3. Binaural masked thresholds expressed as signal to spectral noise density ratios are shown as a function of the masker bandwidth for running-noise maskers. Symbol types are used with the same convention as for Fig. 1. Open symbols represent experimental data, and filled symbols represent the equivalent simulated thresholds

III. DISCUSSION

While the various spectral integration patterns that we observed for the monaural (NoSo) and the binaural conditions (NoSπ) have been reported and modeled previously, that of the binaural condition with either an overall ILD or a reduced masker correlation still needs to be fitted in a model approach. Figure 3 shows a comparison of the behavior of the listeners and the model proposed by Breebaart *et al.* (2001a). The open symbols represent the experimental data and the filled symbols represent the equivalent simulated thresholds. One can see that the model accurately predicts the binaural thresholds (NoSπ), shown by the downward triangles. Especially the wider apparent auditory filter is predicted due the capacity of the model to integrate information from both on-frequency and off-frequency auditory filters. However the model is not able to predict the unusual spectral integration that is observed for the binaural condition with overall ILD (left-pointing triangles) or reduced masker correlation (diamonds). The prediction for these conditions are however correct for the widest masker bandwidth. Effectively for a masker bandwidth of 1000 Hz, the model prediction for both cases rises by an amount from the base NoSπ condition that is in line with the experimental data. In the model this dependence results from an increase of model activity in the internal representation of the reference intervals that is due to the overall ILD or the masker decorrelation that prevent a total cancellation of activity in the binaural processor. A reduction of the masker bandwidth to 1 ERB and smaller values makes the model following the same behavior as for the base NoSπ condition (wider apparent critical band) and therefore predicts the same type of spectral integration. Consequently, it is unlikely that the non-monotonic spectral integration that is observed for the binaural condition with either an overall ILD or a reduction in the masker correlation could be explained in terms of off-frequency listening or across-frequency integration.

This sort of non-monotonic spectral integration has been reported for several other experimental conditions. To stay in the field of tone-in-noise detection, three studies on the monaural detection of a short, high-frequency tone in a noise masker reported the same type of non-monotonic spectral integration. Figure 3 in Oxenham (1998) shows (a) an increase of detection thresholds of a 6-kHz tone for masker bandwidths increasing from 70 Hz up to 1200 Hz and (b) a decrease of thresholds for wider masker bandwidths. Thresholds are reported for 3 signal durations (2, 20, and 300 ms, masker duration 500 ms) and the effect is stronger for the shortest durations. The author comments that "it is not clear what mechanism should underlie this result" (Oxenham, 1998, pg. 1037). For similar experimental conditions (4-kHz signal, 10-ms duration), Bacon and Smith (1991) also reported that detection thresholds decrease by about 2.5 dB for masker bandwidths wider than 1 ERB. Likewise Wright (1997) reported that detection thresholds for a 20-ms (noise) signal centered around 2500 Hz decreased by about 2 dB as the masker bandwidth increased from 1000 to 8000 Hz.

Another case of non-understood spectral integration for supracritical situations was reported by Gabriel and Colburn (1981). They conducted, among others, an experiment to measure interaural correlation detection as a function of the stimulus bandwidth at a reference correlation of 1. One can see in their Figure 4 that thresholds increase with increasing bandwidth beyond the critical band. They comment that this phenomenon is not consistent with the concept of optimal processing. This remark is in line with simulations reported in Breebaart *et al.* (2001b) of these conditions. The model has a central processor which is an optimal detector and, as can be seen in their fig. 3, it predicts a monotonic improvement of the performance with increasing bandwidth but certainly not a decrease of performance. The fact that both these conditions by Gabriel and Colburn (1981) and our NoSπ conditions with a reduced masker correlation involves a major role of correlation in the discrimination process could suggest that the unexpected dependence of the thresholds beyond 1 ERB is somehow related to the influence of interaural decorrelation.

IV. CONCLUSIONS

To conclude this overview on spectral integration, we observe that for subcritical situations, spectral integration for all conditions varies between what one would predict based on a pure energy integration (frozen-noise NoSo and running- and frozen-noise NoSπ, gain of 3 dB/octave) and what one would predict on a more statistical approach (running-noise NoSo, gain of 1.5 dB/octave). For supracritical conditions we observe several behaviors for thresholds as a function of masker bandwidth: (a) constant thresholds (running-noise NoSo), (b) minor spectral integration, reflecting the effect of the apparent wider auditory filter (frozen- and running-noise NoSπ and frozen-noise NoSo), (c) the non-monotonic case of spectral integration where thresholds decrease again for bandwidths beyond 1 ERB (NoSπ with overall ILD or reduced masker correlation). This third situation can not be predicted with a model based on optimal detection and can also not be explained in terms of off-frequency listening. One possibility could be, as it has been suggested previously in a different approach by van der Heijden and Trahiotis (1998), to replace the internal noise that is currently defined in the model by Breebaart *et al.* (2001a) as independent in each individual auditory channel by a bandwidth-dependent internal noise.

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