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Detection of spectrally complex signals : Effect of difference in levels within components

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ABSTRACT

Several authors have demonstrated that detection can be improved by the presence of signal energy in many auditory channels. The subjects were likely to adopt a broadband listening strategy. The results can be reasonably well understood in terms of the multiband energy detector model (Green [1]). Whereas this rule is well established for equally detectable components, it seems to fail for equally intense components (Buus and Grose [2]). In this study, the detection of multicomponent signals that are not equally detectable was investigated precisely as a function of the level difference between components. In the first condition, detection thresholds were determined for seven-tone complex signals (80, 160, 320, 640, 1280, 2560, 5120 Hz), all equally detectable, with random starting phases masked by white noise. In a second condition, variation of the level relation between the components was examined: one of seven frequencies was increased by 5, 10, 15, 20 and 25 dB and then, three of them were increased by 5, 10 and 15 dB. Finally, we investigated the influence of masker type. The masker was a broadband noise with a set of harmonic partials, similar to an interior car sound. We examined the relative effectiveness of broadband noise masker with harmonics compared to white noise.

1. INTRODUCTION

When trying to detect a signal in a noise background, the listener is assumed to make use of a filter with a center frequency close to that of the signal. Only the components in the noise which pass through the filter have an effect in masking the signal. Threshold is assumed to correspond to a certain signal-to-noise ratio at the output of the filter. This set of assumptions has come to be known as the *power spectrum model* of masking. Gässler [3] showed that the power spectrum model was also applicable to complex tones. As the number of tones in the complex was increased, the threshold (expressed as overall level) remained constant until the overall spacing of the tones reached a certain value which the author related to the critical bandwidth. Thereafter, the threshold increased. Gässler suggested that the energies of the individual components are summed within the passband of a single auditory filter. The detection of complex tones is only based on signal energy falling in one band. Even if signal energy extends outside this frequency region, the listener uses only one critical band.

Yet, later experiments could not replicate these findings and let to a slightly different view. Spiegel [4] especially measured the threshold for detecting a noise signal of variable bandwidth centered at 1000 Hz in a broadband background noise masker. The threshold for detecting the signal, plotted as a function of bandwidth, did not show a break point corresponding to the bandwidth of auditory filter, but increased monotonically as the bandwidth increased beyond 50 Hz. Spiegel [4] suggested that the ear is capable of integration over bandwidths much greater than the auditory filter bandwidth.

Langhans and Kohlrausch [5] conducted an experiment similar to the one made by Gässler. They measured the threshold of multitone complexes consisting of sinusoids spaced 10 Hz apart, centered at 400 Hz. The tones were presented in a white noise low-pass filtered at 2000 Hz. In contrast to Gässler's results, Langhans and Kohlrausch [5] observed a continuous decrease in threshold (expressed as level per component) : the thresholds showed a slope lower than the -3 dB per doubling the number of components found by Gässler.

Thus, multiple widely spaced sinusoidal components presented in background noise are better detected than any of the individual components. The subjects are likely to adopt a broadband listening strategy. The auditory system is able to combine information across a wide frequency range in order to improve the detection of a broadband signal. The results can be reasonably well understood in terms of the *multiband energy detector model*, according to the original work of Green [1]. In this model, the components of the signal are assumed to be treated independently the one from the other. Then, the overall sensitivity to a multitonal complex (d_n') is equal to the square root of the sum of the squares of the individual values of d_i'

$$d_n^{'} = \sqrt{\sum_{i=1}^{n} d_i^{'2}}$$

If the sensitivity is the same in each channel stimulated, the resulting sensitivity d_n' for n channels is:

$$d'_n = \sqrt{n} d'_i$$

Consequently, the threshold L_n for a n-component signal (expressed in dB/component) is linearly related to the square root of the number of signal components. The spectral integration is defined as the threshold difference for detection of a tone L_1 (L_1 is the threshold for a single-component signal) as compared to a tonal complex L_n (expressed in dB/component). On the basis of this theory, threshold decreases in 1.5 dB per doubling the number of component, widely spaced.

$$\text{Spectral integration : } L_1 - L_n = 10 * \log\left(\sqrt{n}\right)$$

Buus et al. [6] confirmed this rule for relatively long pure tone signals in wideband noise. They used an uniformly masking noise and measured the detectability of pure tones and of a harmonic complex tone containing 18 equal-amplitude sinusoids spaced roughly one critical band apart. They found that masked thresholds for the single sinusoids (220, 1100 and 3850 Hz) were 43-44 dB SPL and for the 18-component complex it was about 37 dB per component. The complex tone is detectable even if each component is 6.2 dB below its threshold in isolation.

Moore et al. [7] proposed a model for partial loudness, which can be used to predict masked thresholds if the sensitivity to each component is not the same. Moore assumed that it is possible to predict whether a complex sound will be detected in a given background noise by only calculating the thresholds of the most prominent frequency components. This model has practical applications, to warning signals in factories and aircraft (Patterson and Milroy [8]) for example.

The purpose of this paper is to examine the detection of complex tones, equally detectable or not, masked by a broadband noise. The detection of multicomponent signals that are not equally detectable is investigated accurately as a function of the level difference between components. These data have both theoretical and practical implications. From the theoretical point of view, we will examine improvement in detection for multicomponent signals. From the practical point of view, the data may provide a basis to predict masking effects in conditions closer to ecologically significant signals typically more complex.

2. EXPERIMENT 1: DETECTION OF COMPLEX SIGNALS BY WHITE NOISE

The aim of this experiment was to measure spectral integration for multicomponent signals presenting differences in level within components, in a white noise. Grose and Hall [9] measured thresholds for multitonal complexes masked by narrow-band noises, each 20 Hz wide, centered at one of the sinusoidal signal components. They confirmed that the detection is linearly related to √n, similar to results got with broadband unmodulated maskers. The components were at equal physical levels. Bacon, Grimault and Lee [10] conducted a similar experiment but underlined the importance of difference in levels within components to study detection of complex tones. They measured thresholds of four equi-detectable triplets masked by unmodulated or modulated narrow bands of noise, centered at the signal frequencies. They concluded that their results were not influenced by the assumption of equi-detectability. However, this conlusion must be tempered by the fact that the difference between the single-frequency thresholds is probably less than few dB. In the experiment presented here, the detection of multicomponent signals that are not equally detectable was investigated precisely as a function of the level difference between components.

2.1. Stimuli

Detection thresholds were determined for seven-tone complex signals (80, 160, 320, 640, 1280, 2560, 5120 Hz), with random starting phases masked by white noise. In condition 1, the tones were all equally detectable. Then, variation of the level relationships between the components was examined. Firstly, the 640 Hz component was increased by 5, 10, 15, 20 and 25 dB (conditions 2, 3, 4, 5, 6). Secondly, the 320, 640 and 1280 Hz components were increased by 5, 10 and 15 dB (conditions 7, 8, 9).

The masker and the signal were generated in an RPvds (TDT) circuit, including 20 ms cosine-squared rise/fall ramps. Listening intervals were 500 ms in duration. The stimuli were played out by a real-time processor (RP2, TDT), passed through programmable attenuators (TDT PA5) and headphone driver (TDT HB7) before being presented to the listener via a Sennheiser HD650 headset. The stimuli were presented to the subject in diotic conditions. The masker was presented at a level of 55 dB SL. Listeners were seated in a double-walled sound attenuating booth.

2.2. Procedure

Thresholds were measured using an adaptative, three-interval, forced choice (3 IFC) procedure incorporating a three down-one up stepping rule that estimated the 79.4% correct point on the psychometric function. Feedback was provided after each observer response. Level was initially adjusted in steps of 5 dB, and reduced to 2 dB after the second track reversal. The track continued for a total of twelve reversals, and the associated threshold estimate was computed as the average signal level at the last eight track reversals. For each observer the signal conditions were assigned a random order, and thresholds were collected in blocks. Two threshold estimates were collected in each condition. All estimates were averaged to generate a final threshold estimate. If the standard deviation of that average was greater than 3 dB, an additional estimate was obtained and included in the average. Single-frequency thresholds were collected first.

2.3. Subjects

Nine subjects (2 females, 7 males) ranged in age from 22 to 51 years (mean=29 years) participated in experiment 1. They had thresholds at or below 15 dB HL at audiometric test frequencies from 125 to 8000 Hz.

2.4. Results and discussion

The results were consistent across subjects and thus the group mean results are shown in figure 1 and figure 2. In figure 1, the spectral integration or improvement in threshold is plotted for the first six conditions and in figure 2 for the last three. The spectral integration was calculated for each subject and averaged over subjects.

In figure 1, the expected improvement in signal threshold is confirmed for the equally detectable condition ($10\log\sqrt{7}=4.22$). When the 640Hz component is increased by more than 10 dB, the spectral integration tends towards zero. In the 5 dB condition, a spectral integration midway between $10\log\sqrt{7}$ dB and zero is observed. A repeated measures of variance (ANOVA) indicates a significant effect of the condition ($F(N=9, dl=5)=20.63$, $p<0.05$).

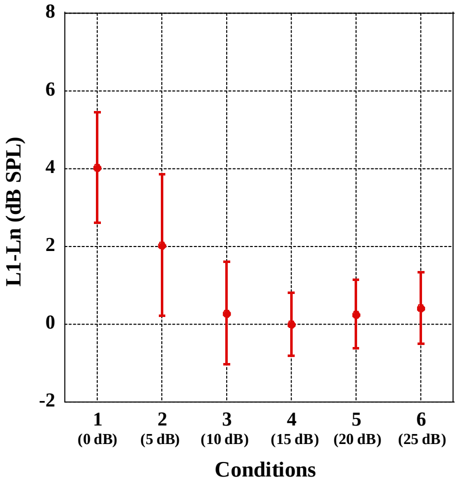

Figure 1. The amount of spectral integration averaged across subjects as a function of signal conditions : first, all equally detectable (condition 1) and then, the 640Hz component was increased by 5, 10, 15, 20, 25 dB (conditions 2, 3, 4, 5, 6).

The result for the equally detectable condition (condition 1) is similar to those reported previously in literature. Each component of a seven-tone complex signal is treated as an independent source of information. This result is in line with the multiband energy detector model.

When the level of one component is increased *sufficiently,* the others are well below their threshold presented in isolation, the individual values of d_i' for these components tend towards zero for a certain value of the level of the prominent component. The overall sensitivity to the multitonal complex (d_n') tends toward the individual value of d_i*'* for the prominent component. Then, only this component play a role in detection. The spectral integration is equal to zero. It is clear that the observed data correspond very well to the prediction beyond a level of 10 dB.

The most interesting aspect of the present results is the spectral integration observed in the 5 dB condition. The detection improves by a factor of less than $10\log\sqrt{7}$ but there is still a detection improvement. The $\sqrt{n}$ rule is not valid. Indeed, the d_i*'* of the lower components contribute less to the overall d_n' than in the equally detectable condition. The data confirme previous result, obtained by Buus and Grose [2]. They have measured thresholds for 5-component complex signals masked by 15-Hz wide bands of Gaussian noise. Each tone was presented at equal level in dB SL (*normalized*) or at equal level in dB SPL (*equal*). They showed that the $\sqrt{n}$ rule seems to fail for equally intense components whereas it is well established for equally detectable components: they measured a 3.3 dB threshold improvement ($10\log\sqrt{5}=3.49$) for the five-component signal in the *normalized* condition, when each tone was individually adjusted in amplitude based on detection threshold, and only 1.5 dB in the *equal* condition.

In figure 2, the spectral integration is plotted as a function of the level relation between components. In the 5, 10 and 15 dB conditions, the observed data are closed to the $10\log\sqrt{3}=2.4$ dB threshold improvement, a difference that is not statistically significant ($t_8=2.89$, $p<0.05$). Only the three components in the seven-tone complex seem to play a role in detection. Once again, the results can be reasonably well understood in terms of the multiband energy detector model.

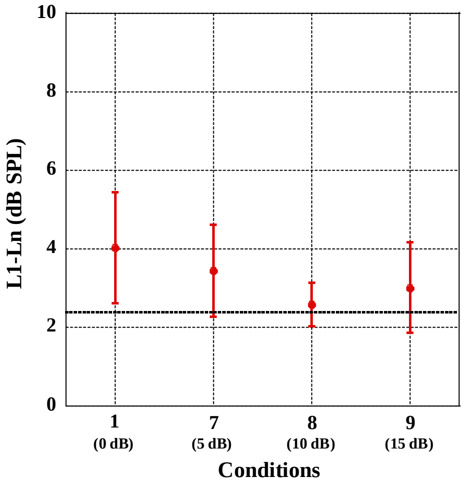

Figure 2. The amount of spectral integration averaged across subjects as a function of signal conditions : first, all equally detectable (condition 1) and then, the 320, 640 and 1280Hz components were increased by 5, 10, 15 dB (conditions 7, 8, 9). The dotted line corresponds to the 2.4 dB of integration that is expected based on the multiband energy detector model.

3. EXPERIMENT 2: INFLUENCE OF MASKER TYPE

The purpose of this experiment was to determine the amount of spectral integration with multicomponent signals masked by an interior car sound. Figure 3 shows the spectrum of such a sound. It can be observed that a lot of harmonics are physically present in the masker. The effect of masker harmonicity on detectability was evaluated by comparing the thresholds obtained with the white noise, described above.

3.1. Stimuli

The masker was the interior car sound shown in figure 3. Detection thresholds were determined for three-tone complex signals (958, 1765, 2828 Hz), all equally detectable (condition 1), with random starting phases. Then, the level relationships between the components was examined. The 1765 Hz component was increased by 5, 10, 15 dB (conditions 2, 3, 4). The masker was presented at a level of 55 dB SL in diotic conditions with the same equipement as in experiment 1.

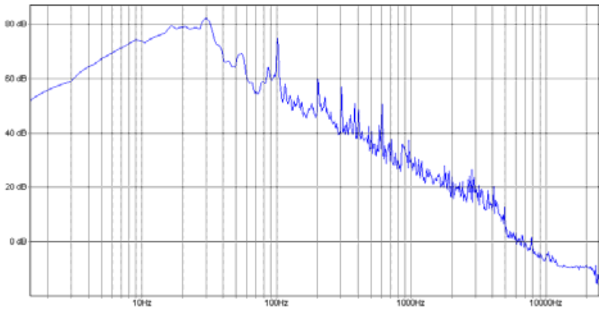

Figure 3. Masker spectrum. The noise was an interior car recording.

3.2. Procedure

As in experiment 1, stimuli were presented in a three-alternative forced-choice paradigm. Listening intervals were 500 ms in duration. First, the threshold for each of the three tones in isolation was measured. The different conditions of level were presented in random order.

3.3. Subjects

Nine subjects (2 females, 7 males) ranged in age from 22 to 51 years (mean=29 years) participated in experiment 2, three of them participated in both experiments. None of the listeners had audiometric thresholds at or below 15 dB HL.

3.4. Results and discussion

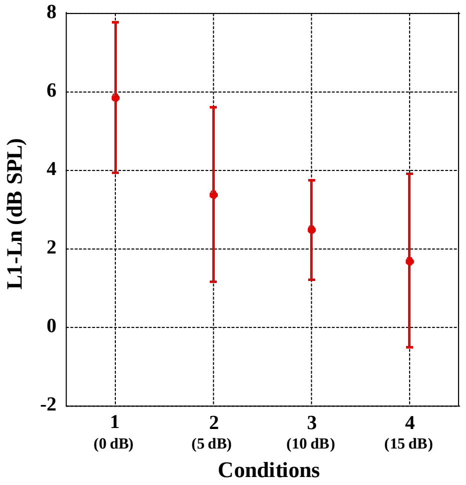

Figure 4. The amount of spectral integration averaged across subjects as a function of signal conditions : first, all equally detectable (condition 1) and then, the 1765Hz component was increased by 5, 10, 15 dB (conditions 2, 3, 4).

In the figure 4, the amount of spectral integration is plotted as a function of signal conditions. The spectral integration was calculated for each subject and averaged over subjects. Even though there is some inter-subject variability, all subjects show the same effects and thus only the average data are discussed. The spectral integration decreases near-linearly to about 2 dB SPL in the 15 dB condition. The spectral integration is 6 dB SPL in the equally detectable condition (condition 1) whereas the theory predicts an amount of spectral integration of 2.4 dB. In contrast to the precedent experiment, the measures did not show the presence of a break point. When the 1765 Hz component is increased by 15 dB, the spectral integration is not yet equal to zero.

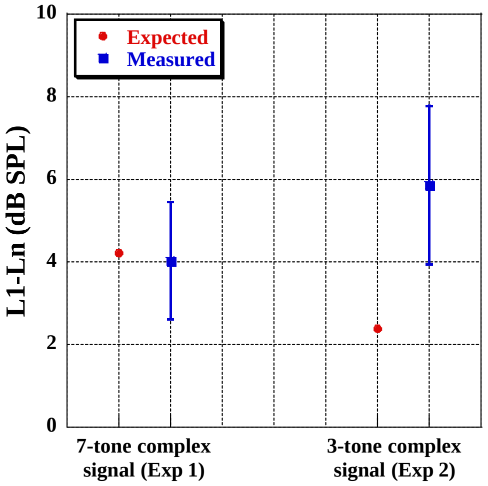

Figure 5. Amount of spectral integration, expected (10log√7=4.2 dB or 10log√3=2.4 dB) and measured, in experiments 1 and 2, in the all equally detectable condition.

In figure 5, the spectral integration, corresponding to the the all equally detectable condition (condition 1), measured in experiments 1 and 2 is compared to the multiband energy detector predictions. In the experiment 2, when all the tones are equally detectable, the observed value is 3.6 dB above the prediction. It is clear that it cannot be related to the √n rule, contrary to the experiment 1. The difference of spectral integration found between the two experiments is important and suggests that there is a cue for signal detection which is not understood by the multiband energy detector model.

One possible explanation for the greater spectral integration is related to the presence of harmonics in the wideband noise. The tonality of the interior car noise can help to detect the multi-component signal. Another possible explanation is related to phase effects associated with variations in masker envelope. Finally, if the slope of the psychometric function are more shallow than predicted by the multiband energy detector model, a given integration in terms of *d'* would correspond to a larger amount of integration in terms of an improvement in dB.

In order to explain these difference in amount of spectral integration, it would be interesting to measure detection thresholds for three-tone complex signals embedded in different maskers. First, the masker could be a white noise with a set of harmonic partials and secondly, a pink noise.

4. SUMMARY AND CONCLUSIONS

Two experiments were conducted, wherein spectral integration was measuring by comparing the threshold of seven-tone signals firstly and three-tone complex signals secondly. The results can be summarized as follows:

(1) In the first experiment, spectral integration was measured for seven-tone complex signals masked by white noise. The result is consistent with the prediction of the multiband energy detector model for equally-detectable complex. When difference in level within components is important, in others words, when the others components are well below their threshold in isolation, only the most prominent components play a role in detection.

(2) In the second experiment, spectral integration was measured as in experiment 1 but the masker was a broadband noise with harmonics, similar to an interior car sound. The data revealed an improvement in detection, that isn't predicted by the multiband energy detector model.

The findings of this experiment corroborate established results concerning the integration of signal energy from across the spectrum, but extend them to apply to the specific configuration wherein components of the multi-tone signal present differences in level. The results of the present study indicate that spectral integration is affected by the type of background noise and other experiments must be conducted to explain the unexpected results.

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