The effect of spectral density and bandwidth on the precedence effect

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Introduction

The precedence effect shows the ability of the auditory system to perceptually suppress reflections such that a single sound is heard at the direction of the leading sound. A low frequency tone is localized on the basis of its interaural phase, but the addition of its delayed copy alters the interaural phase and thus its location. A larger bandwidth is needed to stabilize localization at the lead either through integrating binaural information across frequency or through extracting information from the temporal envelope. Increased spectral density will give rise to faster envelope fluctuations within an auditory filter, thus facilitating the evaluation of binaural cues from the envelope.

The present study investigated the spectral density needed for the precedence effect (PE) for ongoing stimuli of various bandwidths. Stable precedence could not be obtained for unmodulated stimuli for ≤1 Bark bandwidth regardless of the number of tones per critical band (CB). The PE emerges with at least two tones per CB over 3 Bark. No PE was found with one tone per CB which suggests that envelope information within a CB is needed. The echo threshold increases with increasing bandwidth or spectral density, suggesting that within and across-channel information is combined. Low rate amplitude modulation (AM) increases echo thresholds and stabilises the PE.

Methods

Subjects listened to spatialized stimuli via headphones in a sound booth. Precedence effect stimuli were played using virtual acoustics with subjectively selected non-individual head-related transfer functions (HRTFs) [1]. Lead and lag were always played in the horizontal plane from +30° and -30°, respectively. The lag was always a copy of the lead. Stimuli were 300 ms long, resulting in lead and lag to overlap temporally. Echo thresholds (ETs) were determined with an adjustment procedure. Subjects turned on a trackball to vary the time delay between lead and lag. Lead-lag pairs were repeated with an interstimulus interval of 1 sec until the subject confirmed the adjusted ET by pressing a button. The task was to find the largest delay for which a stable, fused image was heard at the lead while anomalous localisation at the lag or a break into two images did not occur for shorter delays. Five normal hearing subjects participated in experiment 1 and four in experiment 2 (<20dB HL in 125 Hz-8 kHz, age 22-35). Subjects were experienced in listening experiments and received at least 20 min training.

Experiment 1: Bandwidth and Density

Stimuli

The aim of experiment 1 was to find the existence boundaries for the PE with regard to spectral bandwidth and density. Stimuli comprised of unmodulated tones placed in equal intervals on the Bark-scale around the center of 500 Hz. Bandwidth was varied from 0.7 to 4 Bark and density from 1 tone per Bark to 5 tones per Bark, c.f. Figure 1. If there was only one tone per Bark it was presented in the band centre while from two tones per Bark tones were also placed at the lowest and highest corner frequency. All tones had the same level and a new, random phase in each trial. Stimulus duration was 300 ms and 50 ms Gaussian slopes were applied. Lead and lag were played 60 dB SPL. Five trials were collected for each condition.

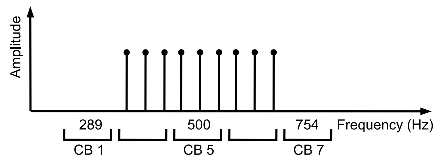

Figure 1: Example stimulus with three tones per Bark over three Bark.

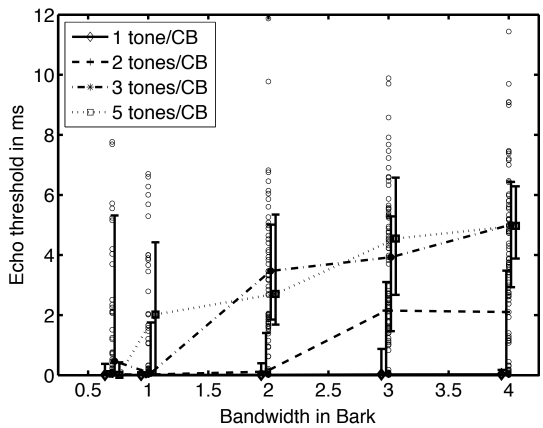

Figure 2: Echo thresholds for unmodulated tones as a function of bandwidth with the number of tones per critical band (CB, bandwidth in Bark) as parameter.

Results

Figure 2 shows results of experiment 1, echo thresholds for unmodulated tones as a function of bandwidth with the number of tones per critical band (CB) as a parameter. For one tone per CB no echo thresholds could be obtained regardless of bandwidth (line, ◊). When two tones are presented per CB (dashed, +), echo suppression becomes possible starting at a bandwidth of 3 Bark. In this case echo thresholds are small with 2 ms. It appears as if the auditory system was able to stabilize localisation at the lead by integrating binaural information or information for the PE across auditory filters. With three tones per CB stable localisation at the lead is possible from a bandwidth of 2 Bark (dashed-dotted, *). The auditory system seems to be able to trade the information gained from across channel processing with information gained from within the filter. This is even more obvious for five tones per Bark where echo thresholds could be obtained with some participants already for a bandwidth of 1 Bark, but not below (dotted, □). When more tones fall within a CB two effects happen: 1) frequency specific phase cancellation which leads to large ILDs and thus anomalous localisation is reduced [2], 2) temporal slopes are steeper, leading to a potential stronger contribution of information evaluated from the envelope.

Our previous study showed that amplitude modulation (AM) can increase echo thresholds, suggesting a contribution of envelope information to the precedence effect even at low frequencies and for ongoing stimuli [3]. Experiment 2 tests if AM can help resolve anomalous localisation.

Experiment 2: Effect of AM

Stimuli

Stimuli of experiment 2 were identical to those of experiment 1 with the difference that the lead was 100% amplitude modulated at 30 Hz or 112 Hz with a start in the AM minimum. The 30 Hz AM-condition will produce sidebands which fall within the CB-filter of the modulated tone while they will be processed in neighbouring filters with 112 Hz AM. Sidebands can be seen as additional tones like in experiment 1; however, they stand in fixed phase relationship to the carrier tone and their level is lower. It remains to be seen if their contribution is different to tones.

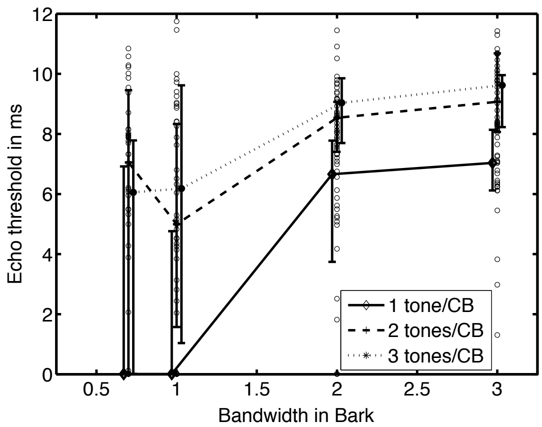

Figure 3: Echo thresholds for tones modulated at 30 Hz as a function of bandwidth with the number of tones per CB as a parameter.

Results

Results of experiment 2 for stimuli modulated at 30 Hz are presented in Figure 3. Echo thresholds are generally larger than without AM. For a 3 Bark wide stimulus with three tones per CB they are as large and reach 8 ms. Surprising is that even with one tone per Bark large ETs of 6-7 ms can be obtained – unlike for unmodulated stimuli. ETs for one tone per Bark are even larger than those for three tones per Bark in the corresponding unmodulated condition which suggests that AM contributes in a different way. However, this needs to be verified with a larger number of subjects. Although variance is high it is striking that ETs can be obtained for some participants for very narrow bandwidth. This is unlike the results for unmodulated tones and it seems that the modulation contributes, stabilises the PE in conditions where anomalous localisation would occur otherwise.

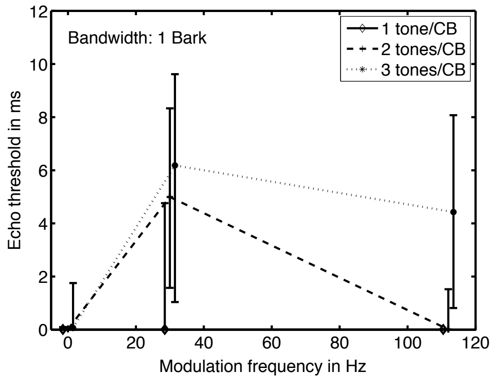

Figure 4: Echo thresholds obtained in experiments 1 and 2 for 1 Bark bandwidth presented as a function of modulation frequency with the number of tones per CB as a parameter.

Figure 2 replots the ETs as a function of modulation frequency when the bandwidth was 1 Bark. At this bandwidth no ETs could be obtained for unmodulated tones regardless of the number of tones per CB. However, despite the narrow bandwidth echo thresholds *could* be obtained with at least two tones per CB. ETs were largest for 30 Hz AM and decreased for 112 Hz AM. This suggests that sidebands should fall within the auditory filter of the carrier to contribute best to the PE. However, if they fall outside the CB filter they may still benefit the PE through increasing the bandwidth or the spectral density of the signal.

Discussion & Conclusions

The results show that the precedence effect could not be obtained for unmodulated sparse complex stimuli where only one or two tonal components fall into a critical band. One example is speech where the voiced part is similar to a harmonic complex tone of 100-200 Hz fundamental frequency. In the absence of amplitude modulation, echo suppression and thus correct localisation in rooms would not be possible. For stimuli with two or more components per CB a minimum bandwidth of several Bark is needed to obtain the PE. Present results suggest that the amplitude modulation intrinsic to speech might provide additional cues. Echo thresholds increased strongly if tonal stimuli were amplitude modulated, and 30 Hz gave the largest effect. With AM echo thresholds of 6-7 ms could be obtained even in a condition with only one tone per Bark – similar to male speech. The results thus show that the lack of spectral density for voiced stimuli can be compensated for by amplitude modulation and a larger spectral bandwidth.

References

[1] B.U. Seeber and H. Fastl. *Subjective selection of non-individual head-related transfer functions.* In: Proc. 9th Int. Conf. on Aud. Display, pp. 259-262. Boston, 2003.

[2] H. Gaskell. *The precedence effect.* Hearing Res. 12(3): 277-303, 1983.

[3] B.U. Seeber. *Interaural grouping and the precedence effect,* In: DAGA '08, pp. 797-798, 2008.