Interaural Grouping and the Precedence Effect

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Introduction

The precedence effect has been viewed in the literature mostly as an independent mechanism of the auditory system with the aim to alleviate interfering effects of reflections. The precedence effect process is mostly thought to be bottom-up, as are the models of it, but some literature also suggests high level influence [1, 3]. Our previous results on precedence with cochlear implant simulations show that the effect has to be seen in the larger context of auditory scene analysis (ASA) [4]. ASA studies the mechanisms that lead to fusion and segregation of sound components into auditory objects. Prominent features for ASA are the common onset of components, common fundamental frequency, and synchronized amplitude and frequency modulation [2]. In a unified theory of auditory perception those Gestalt cues should also govern the precedence effect. At short delays between a leading and a lagging copy of a sound the lag is perceptually integrated, fused with the lead. At delays above the echo threshold (ET) the lag is segregated from the lead. The present study investigates if fusion between lead and lag, as evidenced in the ET, can be influenced by amplitude modulation of lead and lag. The results demonstrate a strong effect of AM, suggesting that fusion and segregation between lead and lag are governed by Gestalt rules. The results further emphasize the importance of envelope cues for the precedence effect while most current models predominantly consider fine structure information.

Methods

Subjects listened to spatialized stimuli via headphones in a sound booth. Precedence stimuli were played using virtual acoustics with subjectively selected non-individual HRTFs. In the first half of the experiment the lead was played from $+30°$ and the lag from $-30°$ in the horizontal plane. Directions were reversed in the second half. 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 until the subject pressed a button. Four normal hearing subjects ($<$ 20 dB HL in 125 Hz-8 kHz, age 22-34, 1 female) participated in the study. Subjects were experienced in listening experiments and received at least 20 min training.

Experiment 1: Stimuli

The carriers for all stimuli were long bursts of white noise (300 ms duration, 100 Hz-5 kHz, 3 ms Gaussian slopes, 60 dB SPL, interstimulus interval $>$ 500 ms) which were generated anew in each presentation. In condition 1 this carrier was used as the lead and lag stimulus, depicted in the top row of Figure 1. In all other conditions the

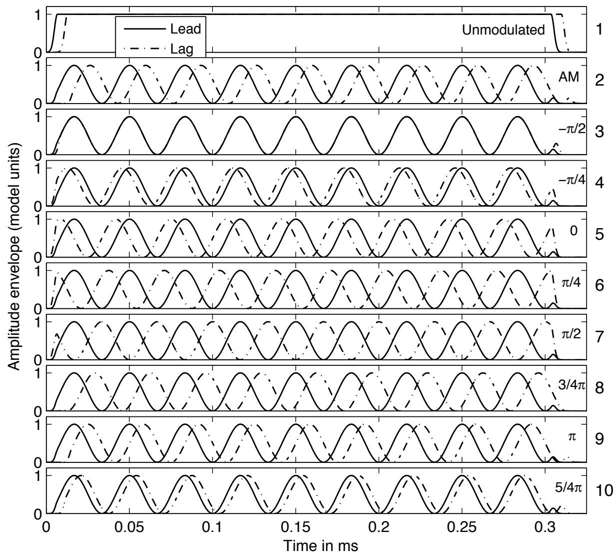

Figure 1: Envelopes of precedence stimuli used in experiments 1 and 2. Experiment 2 employed stimuli 1 and 2 with varying carrier correlations. As plotted the carrier delay is equal to the echo threshold of experiment 1.

carrier was sinusoidally amplitude modulated (AM) at a frequency of 30 Hz and a depth of 100%. The maximum amplitude was left unchanged by the AM. The starting phase of the lead was always $-\pi/2$, i.e. the lead started in the minimum of the AM. In condition 2 the lag was a delayed copy of the modulated lead. In conditions 3-10 the carrier of the lag was delayed and the AM of the lag kept a constant phase difference to the AM of the lead. For example, in condition 3 the AM in lead and lag shared the same starting phase of $-\pi/2$ while in condition 7 the AM-phases differed by $+\pi$, i.e. lead and lag were anti-modulated. Level was fixed across all trials and repetitions. Five trials were taken each for the lead at $-30°$ and $+30°$.

Experiment 1: Results & Discussion

Figure 2 shows ETs for the stimuli of Exp. 1. Modulating the amplitude leads to a significant increase in ET, from 6.1 ms to 9.6 ms. The coherence between lead and lag is unchanged by the AM. One reason for the increase might be the reduced onset slope of the AM-stimulus. However, the delayed occurrence of the modulation peaks in condition 2 should unmask the lag which should lead to a *reduction* of ET. The observed strong increase of ET due to AM is in line with our hypothesis that AM can serve as a grouping cue between lead and lag: The better the auditory system is able to identify the lag as a copy of the lead, the better ASA-mechanisms will be able to perceptually integrate the lag with the lead.

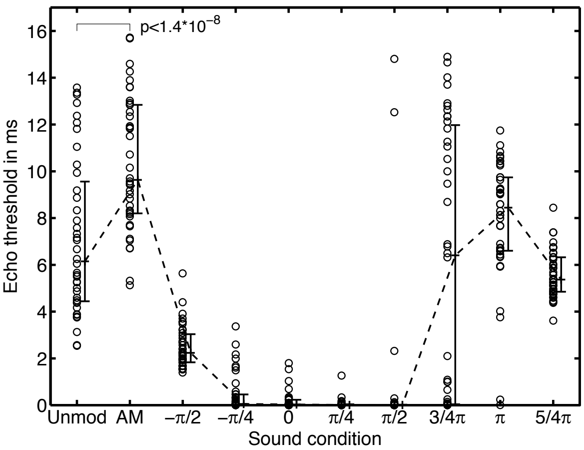

Figure 2: Echo thresholds for stimuli of experiment 1 (Figure 1): individual responses, medians, quartiles.

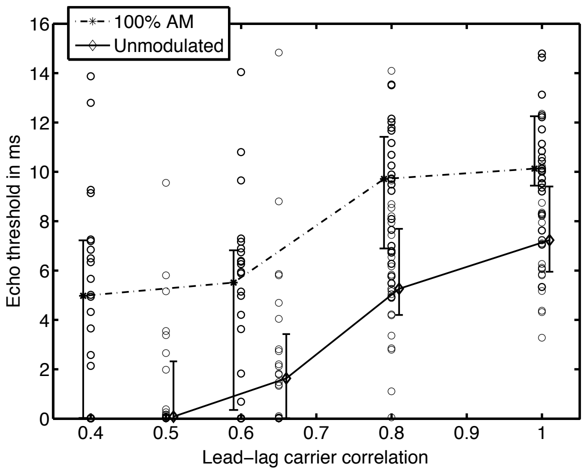

Figure 3: Echo thresholds for unmodulated and modulated wide-band noise for different correlations between the carriers of lead and lag (experiment 2).

In condition 3 lead and lag were co-modulated to enhance fusion of lead and lag. Despite the fact that the carrier delay is not shared by the envelope, a short ET of 2.2 ms was obtained. For longer delays lead and lag become incoherent as the minima of the AM in the lag attenuate the delayed carrier. However, coherence between lead and lag is still high with 0.97 at ET.

In conditions 4-6 the AM is shifted such that the lag either appears long after the lead or before the lead, however, the carrier is delayed. ETs can not be obtained in most cases. This suggests that the auditory system treats the sounds as demonstrating an impossible precedence condition, i.e. the carrier delay and the option of a long envelope delay are ignored and instead lag and lead with closer temporal proximity are grouped together. One reason for why no ETs can be obtained might be the above mentioned attenuation of the lag in the AM-valleys which leads to a reduced coherence at longer delays. However, at ET coherence is still 0.90 in cond. 4.

In condition 7 lead and lag are anti-modulated. This can be seen as an envelope delay of 16.7 ms or as the strongest suppression of lead-lag envelope grouping. Very few responses occurred at long delays, indicating that there is only a minimal chance to obtain ETs at those delays. Nearly all responses were around 0 ms suggesting that the lag was always audible and not suppressed. Responses in condition 8 are bimodally distributed. A fit of two Gaussian distributions using the Generalisation-Maximization algorithm suggests cluster means of 11.0 ms and 0.3 ms. The envelope delay was 12.5 ms. Lead-lag coherence was 0.8 at ET. At shorter carrier delays coherence might be reduced, leading to the breakdown of fusion. For conditions 9 and 10 consistent ETs can be obtained. They seem to follow the envelope delay: 8.4 ms for 8.3 ms delay in condition 9 and 5.4 ms for 4.2 ms delay in condition 10.

The results demonstrate the high importance of envelope cues for the precedence effect even for ongoing stimuli: the envelope is able the enhance ETs, shorten them, or even to obliterate fusion of lead and lag. Experiment 2 is designed to study the influence of lead-lag carrier coherence against the grouping by envelope modulation.

Exp. 2: Stimuli, Results & Discussion

Experiment 2 used the stimuli of conditions 1 and 2 of exp. 1 in the same precedence paradigm. The correlation between the carrier noises for lead and lag was varied. Three trials were taken.

Figure 3 shows ETs for umodulated (cond. 1) and amplitude modulated (cond. 2) noise for various carrier correlations between lead and lag. In general, ETs become shorter the smaller the correlation between lead and lag carriers. Without modulation ETs can be determined down to a carrier correlation of about 0.65. Exp. 1 showed that AM increases ETs for correlated carriers. Exp. 2 confirms this and adds that this excess is maintained at lower carrier correlations. At a carrier correlation of 0.4 the ET is 5.0 ms with AM, while no thresholds could be obtained without AM.

In the view of auditory scene analysis the results show that the grouping by carrier correlation can be traded and even overcome by envelope grouping. The envelope cues have a strong impact on the precedence effect even for ongoing sounds – making lag suppression possible for correlations and delays at which it was not without AM.

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