Precedence effect with piano tones of same and different timbre

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Listeners in reverberant rooms are usually unaware of the numerous reflections reaching their ears. The reflections are not perceived separately, but are fused into a single image that appears to come from the direction of the sound source. This perceptual phenomenon in which the apparent direction of a sound source is dominated by the first arriving wave front, is known as the "precedence effect" [e.g. 1]. A typical arrangement to study this effect consists of a leading sound coming from one spatial direction and a single reflection (lag sound) coming after a certain delay from a different direction. Lead and lag stimuli in such studies are often exactly the same sound (identical waveform and equal amplitude). In realistic situations reflections are rarely identical to the source. Recent studies [2, 3] in fact show that the coherence of lead and lag sounds is not a necessary condition for precedence. Yang and Grantham [3] suggest that in free-field presentations precedence is primarily based on a spectrally anchored similarity between lead and lag. However, two important questions remain:

a. What amount of spectral similarity is necessary?
b. What signal parameters determine spectral similarity?

The second question is particularly important in the field of musical acoustics. Recent investigations [4] revealed the auditory cues that are responsible for perceptual dissimilarities between piano tones, and a psychoacoustic model for calculating these dissimilarities has been developed. Already having an answer to the second question led to the decision to study the first question with synthesized piano tones. In the case of musical stimuli the following two questions, that are addressed in the present study, are of interest with regard to spectral similarity:

a. Does precedence fail for instrument tones with distinct timbre dissimilarities?
b. Is similarity underlying precedence reversible, that is, does precedence depend on which one of two piano tones with distinct timbre dissimilarities is presented as the lead and which one as the lag?

1. Experiment I: Echo threshold for piano tones

The synthesized piano tones used in this study differ in two important aspects from the stimuli that are commonly used in precedence studies: (a) Instead of using clicks, noise bursts or sinusoids, quasi-harmonic natural complex sounds with time-varying spectral envelopes and natural onsets were used. (b) The duration of the piano tones was 500 ms (about a quarter note in a 120 Allegro beat) and thus much longer than typical echo delays in normal rooms. That means that lead and lag sounds temporally overlapped for most of the presentation time. Because of these differences to typical precedence stimuli, the echo threshold for the piano tones was assessed in a first experiment with three subjects between 19 and 29 years of age. They all had hearing thresholds within normal limits.

The experiment was conducted in an anechoic chamber in which different virtual scenarios can be created with a set of 12 computer controlled loudspeakers. The same piano tone (equal amplitude and waveform) was presented as a lead-lag pair with varying delays from virtual locations at a distance of 6.1 m from the subject and 38.5° of separation between the lead and lag. On each trial, a single lead-lag pair was presented from different directions relative to the listener. According to Blauert's definition of the echo threshold [1], subjects had to report whether they perceived "one fused sound" or "two or more spatially separate sounds". The subjects were instructed to face directly ahead and not move the head during the run. The results show that the 50% echo threshold [5] for this kind of sound is about 7 to 8 ms and thus within the range of thresholds measured for clicks, but well below the measured thresholds of 20 to 50 ms for ongoing speech or music [1]. Simulating the attenuation of the lagging sound due to the longer path according to the 1/r-law for spherical waves increases the measured echo threshold of the piano tones to about 15 to 26 ms.

2. Theoretical approach and hypothesis

The theoretical approach to estimate the amount of spectral similarity necessary for precedence is based on the conceptualization of the precedence effect as a decision-making process that is affected by ongoing auditory stimulation [6]. Various investigations [e.g. 5] have shown that the echo threshold is raised by several milliseconds if a lead-lag click stimulus is repeated over and over again. This phenomenon is referred to as buildup in precedence. Echoes are thought to carry information about the acoustic environment. During the repeated presentation of a lead-lag pair this information is picked up by the listener to form expectations about what will be heard. It has been shown [6] that violating this expectation by introducing sudden, unexpected changes in the echo leads to a decrease of the raised echo threshold. Based on these findings the following hypothesis was formulated by Clifton et al. [6]:

> *The precedence effect is a dynamic process, subject to listeners' expectations about what a* ***plausible*** *echo should be.*

The plausibility of an echo in a buildup condition is given by the probability of a sudden environmental change. In the case of baseline precedence, that is for just one isolated lead-lag presentation without continuous repetitions, the listener has not yet received the information about the specific acoustic environment necessary to build up such an expectation. Hence, the plausibility of an echo in baseline precedence can not be based on information about the specific acoustic environment. In order to address the question of what makes an echo plausible in baseline precedence the following new hypothesis for baseline precedence is formulated:

> *General knowledge about properties of real-world reflections is an important factor that determines the plausibility of an echo in baseline precedence.*

According to the physical laws of sound wave reflections, only specific changes between an incident sound wave and its reflection are possible and thus plausible. Examples of plausible changes are an overall attenuation of the reflected wave, and a decrease of energy in frequency bands of the reflected wave by means of passive filtering. On the other hand, a resolvable increase of energy in frequency bands of the reflected wave or a frequency-shift of its spectral components are examples of implausible changes.

3. Experiment II: Influence of differences in timbre on the precedence effect

In order to estimate the amount of spectral similarity that is necessary for precedence a second experiment was conducted in the anechoic chamber with the synthesized piano tone of experiment I (tone A in Fig. 1) and two variations of this tone (tones B and C in Fig. 1).

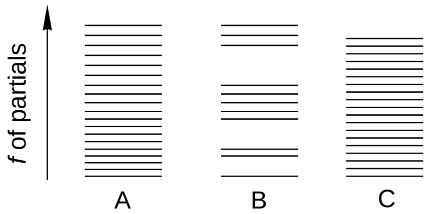

Fig. 1: *Schematic view of the three types of piano sounds used in the second experiment.*

The variation B was derived from the original piano tone A by attenuating selected partials and thus simulating a passive filtering operation that would be caused by a frequency-dependent coefficient of reflection. The variation C was created from the quasi-harmonic piano tone A by changing the slightly inharmonic relationship between the partials to a perfect harmonic relationship. Such a frequency shift of the partials could never be produced by a realistic reflection. With these three tones that had clearly audible timbre dissimilarities four lead-lag pair combinations were selected. These pairs were chosen such that two pairs had a plausible and two pairs had an implausible echo according to the above-mentioned hypothesis for baseline precedence. The selected pairs and their spectral dissimilarities are depicted in the first two columns of Table I.

Table I: *Lead-lag pair combinations of the three piano tones A, B, and C, that were used in experiment II. For further information see text.*

	dissimilarity	lead-lag	ΔL (lag-lead)
plausible	none	A - A	-1.8 dB
	missing partials	A - B	-3.4 dB
implausible	more partials	B - A	-0.2 dB
	shifted freq.	A - C	-1.8 dB

All lagging sounds were attenuated according to the 1/r-law for spherical waves. By simulating the decreased level of realistic echoes due to their longer travelling path, even in the case where the lag had more partials than the leading sound the overall level of the lag was still smaller than that of the lead. The differences between the overall level of the lag and lead stimuli are shown in the third column of Table I for a delay of 4 ms between lead and lag.

Method. The experiment was conducted in the anechoic chamber using again the computer-controlled loudspeakers to simulate the desired virtual environments. The leading stimulus was presented from a virtual location in front of the listener at a distance of 6.1 m coming from either +2.75˚ to the right or -2.75˚ to the left of the subject. The lagging sound was presented from either +27.5˚ to the right of the corresponding lead or -27.5˚ to the left of the lead. The delay between the lead and lag stimuli was always 4 ms. Experiment I revealed that the echo threshold for piano tones is about 7.5 ms when the lagging stimulus is presented at the same level as the lead and even larger (about 15 ms) when the lag is attenuated according to the 1/r-law. Hence, by choosing a delay of 4 ms for each trial, the precedence effect should be active for any of the selected lead-lag combinations. To prove for which of the four selected lead-lag combinations from Table I the precedence effect fails due to the timbre difference between the source and echo, these lead-lag combinations were presented to the subjects in a randomized order. On each trial, a single lead-lag pair was presented, and the subjects' task was to report whether they perceived "one fused sound" or "two or more sounds". Four subjects between 24 and 39 years of age with normal hearing in both ears participated in this experiment.

Results. For each of the four possible lead-lag combinations the percentage of trials on which listeners reported "two or more sounds" is plotted in Fig. 2 averaged across subjects.

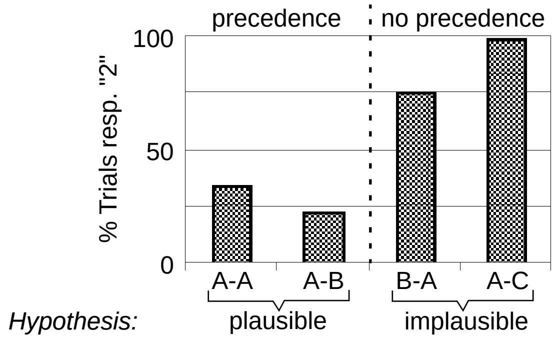

Fig. 2: *Percentage of trials on which listeners reported "two or more sounds" for each of the four lead-lag combinations depicted in Table I.*

The results show that the precedence effect was active for the two combinations that, according to the hypothesis for baseline precedence, had a plausible echo as the lagging stimulus (combinations A-A and A-B). But precedence failed for the two cases with implausible echoes (combinations B-A and A-C). Further, the two combinations A-B and B-A, having the same timbre dissimilarity and differing only in the plausibility of their echoes, suggest that the amount of spectral similarity necessary for precedence is not reversible. In summary, the results suggest that timbre similarity per se is not a necessary condition for precedence and support the hypothesis of plausibility formulated for baseline precedence.

4. Conclusions and summary

The results of this study show that precedence does not necessarily fail for instrument tones with distinct timbre dissimilarities. The amount of spectral similarity or overlap that is essential for baseline precedence in free-field presentations depends on whether or not the spectral dissimilarities may be explained by a realistic and thus plausible change caused by a reflective surface. As a plausibility decision seems to be key to baseline precedence, the precedence effect depends on which of two sounds is presented as the lead and which as the lag.

References

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