Do listeners' expectations or similarity between a signal and its echo determine the strength of precedence?

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A single sound source produces under normal room conditions a large number of reflections from the nearby surfaces. Listeners in such a room are, however, normally not aware of the numerous time-delayed echoes. On the contrary, the reflections are in general not perceived separately, but are fused into a single image that appears to come from the direction of the sound source. This perceptual phenomenon is known as the precedence effect [e.g. 1, 2]. The shortest delay at which the echo becomes audible as a separate image is called echo threshold [2].

According to different studies the precedence effect seems to be governed by cognitive processes in higher centers of the nervous system. These decision-making processes control the strength of the precedence effect by evaluating both, (a) the spectrally anchored similarity between a signal and its echo, and (b) the immediate prior stimulation from which listeners form "expectations" about the sounds that can occur in the given environment. In the present paper the relative influence of these two factors on the strength of precedence is investigated.

1. Motivation

In recent years, the precedence effect has been conceptualized as a dynamic process that is subject to listeners' expectations about what a *plausible* echo should be. The factors that determine the plausibility of an echo are different for the two classical conditions used to study precedence, namely baseline precedence and buildup precedence. A typical arrangement to study the precedence effect consists of a leading sound source from one spatial direction and a single echo (lag sound) coming from a different direction after a short delay. In the so-called baseline precedence condition only one lead-lag pair is presented per trial. A buildup condition is generated by presenting the lead-lag pair over and over again (conditioning train). Various investigations [1] have shown that the echo threshold is raised by several milliseconds in such a buildup condition.

The plausibility of an echo in baseline precedence is mainly determined by general knowledge about properties of real-world reflections [3]. 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. Hence, the dissimilarity between the lead and lag sound determines the plausibility of the lag. The plausibility of an echo in a buildup condition, on the other hand, is given by the probability of a sudden environmental change. The information about the acoustic environment that is picked up by the listener during the repeated presentation of a lead-lag pair in the conditioning train is used by the listener to form an expectation about what will be heard next. The plausibility of the echo in the following test pair is thus determined by the previous auditory stimulation.

Based on these findings the plausibility of an echo in a test pair consisting of a lead and a lag sound is determined by its baseline plausibility, i.e. the plausibility of its dissimilarity to the leading sound, and by its buildup plausibility, i.e. the listeners' expectations for this echo due to the preceding auditory stimulation. The question that has not been addressed until now is if the plausibility of such an echo, and thus the strength of precedence for this test pair, is mainly determined by the baseline or buildup plausibility of the echo. In other words, is precedence of a test pair mainly determined by the dissimilarity between the lead and lag sound or by the listeners' expectations formed during the prior stimulation? Based on this question one could further ask if (a) it is possible to affect a plausible lead-lag pair with a strong precedence effect by presenting an improbable environmental change, and (b) if it is possible to buildup precedence for an implausible lead-lag pair through repeated presentation of this pair and thus asserting the existence of such an acoustic environment.

Although the above stated question has never been addressed directly, some partial responses or indications for a response can be found in literature. McCall et al. [4] have shown that changing the spectrum of the lagging sound in the test pair causes a breakdown of the adapted echo threshold (buildup through repeated prior stimulation with a conditioning train) to the echo threshold as measured in baseline condition. As their investigations were conducted with lead-lag delays around the measured baseline echo threshold, it is not possible to conclude if such a spectral change that simulates a sudden environmental change would also affect a lead-lag pair in a strong baseline condition. It is, therefore, not possible to conclude form their results if precedence is mainly determined by the baseline or buildup plausibility. In this sense, Freyman et al. [5] have demonstrated that under extreme conditions the echo threshold of a lead-lag pair with strong baseline precedence may be decreased below the baseline threshold by presenting a conditioning train that consists only of a lead. They propose a perceptual contrast effect as the most likely explanation for this observation, leaving the question open if by introducing a less extreme environmental change, that would not evoke a contrast mechanism, the baseline plausibility of a lead-lag pair could be disrupted. An indication that the plausibility of an improbable environmental change can be "taught" to a listener by repeated presentation of the same, has been shown by Blauert and Col [6]. However, this investigation does not respond to the question if precedence can be buildup for an implausible lead-lag pair by repeated presentation of the same. In the following, an experiment is described to investigate directly the relative importance of baseline and buildup plausibility for a lagging sound in a test pair.

2. Experimental method

In order to examine if the plausibility of a lagging sound in a test pair is primarily determined by the plausibility of its dissimilarity to the leading sound or by the buildup environmental expectations that are formed during a preceding conditioning train the following setup was used: Each trial consisted of a conditioning train comprising ten repetitions of a lead-lag pair and a subsequent test lead-lag pair. The leading sound on each trial remained the same for the conditioning train and the test pair, but the lagging sound was in most cases changed from the conditioning train to the test pair. The pause between the lead-lag pairs in the conditioning train was 500 ms and a pause of 750 ms separated the conditioning train from the test pair. The delay between all leading and lagging sounds was chosen such that a strong precedence was guaranteed for all but one of the used lead-lag combinations. The value was determined in a separate experiment as described in the next section.

The parameter that was varied form trial to trial was the plausibility of the lagging sound in the test pair. This was done by either changing its baseline plausibility, i.e. the plausibility of its dissimilarity to the leading sound, or by manipulating the buildup plausibility, i.e. disrupting or reinforcing the buildup expectations of the listener formed during the preceding conditioning train. On every trial subjects were asked to report whether they perceived "one fused sound" or "two or more separate sounds" during the test pair.

Stimuli. The sounds used in this study were a synthesized piano tone of 500 ms duration (tone A in Fig. 1) and two variations of the same (tones B and C in Fig. 1). The variations B and C were derived from the original piano tone A by attenuating different se-

lected partials and thus simulating two different passive filtering operations that would be caused by two different frequency-dependent coefficients of reflection. Note that the partials contained in the tone B were not present in the tone C, and vice versa.

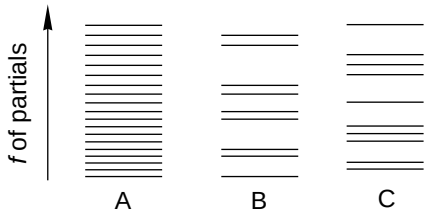

Fig. 1: *Schematic view of the three types of piano-like sounds used in the present experiment.*

With these three tones that had clearly audible timbre dissimilarities five lead-lag pair combinations were selected. Four lead-lag pairs (AA, BB, AB and AC) had a plausible echo according to the plausibility hypothesis for baseline precedence [3] and one pair (BA) had an implausible echo which could never be produced by a realistic reflective wall. In a separate experiment which was conducted in an anechoic chamber as described in [3] the echo threshold of the four plausible lead-lag pairs was measured to be about 7 to 8 ms under baseline conditions. The echo of the implausible pair was even for a delay of 2 ms perceived as a spatially separate sound.

Based on this result a delay of 4 ms was chosen for all leading and lagging sounds in the conditioning train and the test pair of the present experiment. In this way a strong precedence was guaranteed for all lead-lag pairs in which the lagging sound is a plausible echo according to the plausibility hypothesis for baseline precedence.

Tested combinations. Four different conditions need to be verified when examining the plausibility of the lag sound in the test pair: (1) Both, baseline and buildup plausibility reinforce the plausibility of the lag in the test pair as a true echo of its preceding lead sound (Table I, row 1). (2) Only baseline plausibility suggests that the lag in the test pair is a true echo of the lead. The conditioning train on the other hand stimulates an acoustic environment that is suddenly changed in the test pair rendering the lagging sound in the test pair as an implausible echo according to the listeners' prior experience (Table I, rows 2 and 3). (3) Only buildup plausibility suggests that the lag in the test pair is a plausible echo according to the listeners' expectations. On the contrary, the dissimilarity between the leading and lagging sounds in both the conditioning train and the test pair suggest that the lag is not a plausible echo of the lead (Table I, row 4). (4) Both, baseline and buildup implausibility reinforce the implausibility of the lag in the test pair and prevent its suppression, thus enabling the listener to perceive the lag as a spatially separate event (Table I, row 5).

Table I: *Tested combinations of lead-lag pairs in the conditioning train and the test pair.*

Buildup plausibility	Baseline plausibility	Train lead-lag	Test lead-lag
yes	yes	B - B	B - B
no	yes	A - A	A - B
no	yes	A - C	A - B
yes	no	B - A	B - A
no	no	B - B	B - A

Listening environment. The experiment was conducted in an anechoic chamber using computer-controlled loudspeakers to simulate different virtual environments. The leading sounds of both, the train and test, were presented from the same direction within a trial. The same was true for the lagging sounds. The leading sounds were presented from either +2.75˚ to the right or -2.75˚ to the left of the subject. The lagging sounds were presented from either +27.5˚ to the right or -27.5˚ to the left of the lead. 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 lead the overall level of the lag was still smaller than that of the lead.

3. Results

For each of the five tested combinations the percentage of trials on which listeners reported "two or more sounds" during the test pair is plotted in Fig. 2 averaged across the 4 subjects.

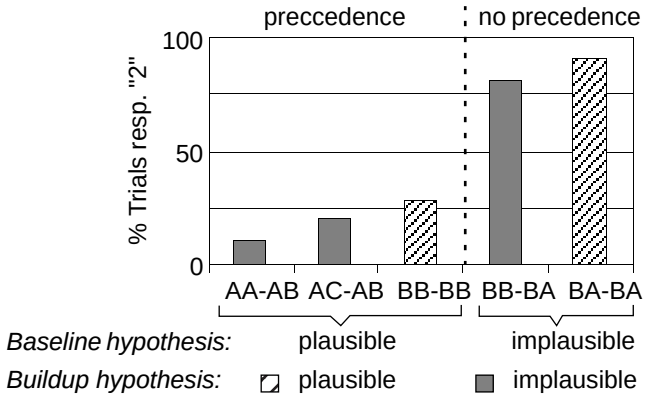

Fig. 2: *Percentage of trials on which listeners reported "two or more sounds" during the test pair (five tested combinations as depicted in Table I).*

The results show that the precedence effect was active for the three combinations that, according to the hypothesis for baseline precedence, had a plausible echo as the lagging stimulus in the test pair. The implausible environmental change in two of these combinations (AA-AB and AC-AB) did not breakdown the baseline precedence. If the lag in the test pair was implausible according to the baseline hypothesis, not even the attempt to raise the listeners' expectations of this implausibility by repeating the presentation of this lead-lag pair in the prior train would activate the precedence mechanism (BA-BA).

4. Conclusions and summary

The results of this study suggest that precedence of a test lead-lag pair is primarily determined by the baseline plausibility requirements, i.e. the plausibility of the lead-lag dissimilarity, and secondly by buildup expectations in the prior auditory stimulation. Changing the information about the acoustic environment does not affect baseline precedence of a real echo, unless a contrast effect as in [5] is evoked by the prior stimulation. On the other hand, it seems not possible to buildup precedence for a lead-lag pair that has an implausible lag according to baseline precedence by building up the listeners' expectations through repeated presentations of this pair.

References

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