

Dynamic processes in the precedence effect

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Three experiments were conducted to investigate the dependence of echo suppression on the auditory stimulation just prior to a test stimulus. Subjects sat in an anechoic chamber between two loudspeakers, one which presented the "lead" sound, and the other the delayed "lag" sound. In the first experiment, subjects reported whether or not they heard an echo coming from the vicinity of the lag loudspeaker during a test click pair. In seven of nine listeners, perception of the lagging sound was strongly diminished by the presence of a train of "conditioning" clicks presented just before the test click. Echo threshold increased (subjects were less sensitive to echoes) as the number of clicks in the train increased from 3 to 17. For a fixed number of clicks, the effect was essentially independent of click rate (from 1/s through 50/s) and duration of the train (from 0.5 through 8 s). A second experiment demonstrated a similar buildup of echo suppression with white noise bursts, regardless of whether the bursts in the conditioning train were repeated samples of frozen noise, or were independent samples of noise. Using an objective procedure for measuring echo threshold, the third experiment demonstrated that both lead and lag stimuli must be presented during the conditioning train in order to produce the buildup of suppression. When only the lead sound was presented during the conditioning train, the perceptibility of the lag sound during the test burst appeared to be enhanced.

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INTRODUCTION

Humans are usually unaware of the numerous reflections reaching their ears when sounds are produced in enclosed spaces. In normal-sized rooms, the original signal and the reflections are not perceived separately, but are fused into a single image that appears to come from the location of the original sound source. Although we are able to notice differences in sound quality when in rooms with different amounts of reverberation, the apparent direction of the sound is almost always dominated by the first arriving wave front. This perceptual phenomenon is known as the "precedence effect" or the "law of the first wave front" (Wallach *et al.*, 1949; Zurek, 1987).

To simplify the study of this complex phenomenon, much of the experimental work on the precedence effect has been conducted with single echoes. The situation is often created in an anechoic room using two loudspeakers, one to produce the original or leading sound, and the other to produce the reflection or lagging sound. Blauert (1983) described a continuum of perceptual changes that take place as the delay of the lagging sound is increased. When the delay is very short (less than 1 ms), the listener perceives one sound that appears to originate from a position in between the two speakers. The exact position is determined by a combination of delay and level differences (e.g., Leahey, 1957). This has been called summing localization (Warncke, 1941). As the delay is extended just beyond 1 ms, the precedence effect increases in strength and the perceived direction is dominated by the leading sound. However, although only one image

is perceived, listeners usually have little difficulty distinguishing between trials in which the lagging sound is present or not present (Blauert, 1983). This is because the presence of the lagging sound can alter the loudness, pitch, quality, and spatial extent of the auditory image. Also, under experimental conditions listeners can be quite sensitive to small changes in the azimuth of the lagging sound (Perrott *et al.*, 1989). Hartmann (1983) and Rakerd and Hartmann (1985, 1986) have shown that the presence of reflections degrades localization accuracy and precision relative to an anechoic environment, but, as long as the signal has a reasonably steep onset, the perceived location is dominated by the location of the original sound.

As the delay of the lagging sound is increased still further, the auditory image begins to spread toward the lag location (Perrott *et al.*, 1989), then breaks apart into two spatially distinct images, one corresponding to the leading sound and the other to the lagging sound. The shortest delay at which this occurs has been called the *echo threshold* (Blauert, 1983, pp. 224–225), which could be considered the upper boundary of the precedence effect. The echo threshold varies widely, from 5–10 ms for clicks (Thurlow and Parks, 1961), to more than 50 ms for speech (Lochner and Burger, 1958). The strength of echo suppression depends on a variety of factors, including the frequency of a stimulus (Schubert and Wernick, 1969; Kirikae *et al.*, 1971), the duration of the stimulus (Schubert and Wernick, 1969), the frequency relationships between lead and lag (Blauert and Divinye, 1988), and the specific task and instructions given to subjects (see Blauert, 1983, pp. 226–227).

While the influence of stimulus characteristics on echo threshold has long been recognized, dynamic changes in the threshold as a function of ongoing stimulation have only recently been noted. Clifton (1987) observed that if the locations of the lead and lag sounds were reversed during a long train of click pairs, echoes were often heard from the new lag loudspeaker even when they were not perceived before the switch. In other words, listeners localized the sound as coming from only one loudspeaker before the switch in lead and lag loudspeakers, but from both loudspeakers just after the switch. As the click train continued after the switch, subjects reported that the echo faded away. Clifton and Freyman (1989) observed that even before the switch subjects sometimes heard echoes at the location of the lagging loudspeaker immediately after trial onset, but that these became inaudible as the click train progressed. Thus the abrupt switch in lead and lag location is not required for subjects to perceive the echo fading away during a click train. Thurlow and Parks (1961) also noted that during a train of click pairs echo suppression "...did not appear immediately, but built up over a period of 1 to 2 sec." (p. 11). However, most investigators studying the precedence effect have not reported this "buildup" in echo suppression, probably because most experiments consist of isolated stimuli rather than stimulus trains.

Clifton and Freyman (1989) quantified the change in echo perceptibility after the switch in lead and lag loudspeaker locations by having subjects hold down a button as long as an echo was heard at the lagging loudspeaker. In that study, the rate at which clicks were presented during the train varied between 1 and 4 clicks/s. The echo faded out after the switch at all click rates, but more slowly at slower click rates, taking up to 10 s at a rate of 1/s. However, when the data were plotted as a function of the number of clicks after the switch, as opposed to the time elapsed since the switch, the rate effect disappeared. Thus the fadeout of the echo appeared to be dependent upon the number of clicks presented after the switch.

The current study used a different procedure to study the dynamic nature of echo suppression. Unlike our earlier study (Clifton and Freyman, 1989), where subjects recorded their moment-to-moment perceptions during a click train by pressing and releasing a button, in the current study a single response ("echo" or "no echo") was obtained on each trial. The procedure was similar to that described by Wolf (1988), and was used by Freyman *et al.* (1989) on an ear-phone study of the precedence effect. Subjects heard a click train ("the conditioner") and, then, after a brief period of silence, the test click. On every trial subjects were asked to report whether or not they heard an echo during the test click. Characteristics of the conditioning click train were varied to evaluate their influence on the echo threshold for the test click.

The current study consisted of three experiments. The first of three phases in experiment 1 was a preliminary screening study in which the echo threshold for an isolated test click was compared with that obtained for a test click preceded by a train of 9 clicks at a rate of 4 clicks/s. The second phase examined the effect on echo threshold of three

variables of the conditioning click train: (a) the number of clicks in the train; (b) the duration of the train; and (c) the click rate during the train (ranging from 1/s–16/s). The third phase of experiment 1 determined whether the buildup of echo suppression is experienced at very fast click rates (50/s), where the conditioner is perceived more as a low-frequency buzz than as a train of separate clicks. In experiment 2, the stimuli used to produce the buildup of suppression were extended to include trains of white noise bursts, which were either identical to one another or were independent samples of noise. Experiment 3 investigated whether both lead and lag stimuli must be present during the conditioning train in order for the buildup of echo suppression to be produced.

1. EXPERIMENT 1: CLICK TRAINS

A. Method

1. Stimuli and apparatus

Stimuli were pairs of computer-generated 150- μ second pulses presented from two channels of a D/A converter (TTES QDA1). The outputs of the two signal channels were low-pass filtered at 8500 Hz (TTE J1390), attenuated (TTES PAT1), amplified (NAD 2100), and connected to a pair of matched loudspeakers (Realistic Minimus 7), situated in a $4.9 \times 4.1 \times 3.12$ -m anechoic chamber. The floor, ceiling, and walls of the chamber were lined with 0.72-m foam wedges. Subjects sat near the center of the room with the loudspeakers situated at 45 deg left and right of midline at distance of 1.9 m. The center of the loudspeakers was 1.04 m above the wire mesh floor of the anechoic chamber, the approximate height of the average subject's ears while seated in the chair. The stimulus level was measured by presenting trains of clicks at a 4/s rate. With the microphone placed at the position of the center of the listeners' head, and the meter response of a B&K 2204 SLM set on "impulse," the measured level was 58 dBC. This was a comfortable listening level for subjects.

2. Procedures

On each trial a "test click" was presented from both loudspeakers, with the left loudspeaker delivering the leading click, and the right loudspeaker, the lagging click. The subjects' task was to report, using a response button box held on the lap, whether or not they heard a sound coming from the vicinity of the right loudspeaker during the test click. Subjects were instructed to face directly ahead, but were not physically restrained in any way.

In most conditions, the test click was preceded by a train of click pairs that were identical to the test click. Thus each trial consisted of the click train, followed by a brief period of silence (750 ms), and then the test click (see Fig. 1). Subjects were instructed to base their judgments only on what they heard during the test click and not on their perceptions during the preceding click train. The interclick interval and the number of clicks in the train were fixed during a block of trials, while the lag click delay varied from trial to trial within a block. The delays ranged from 2–14 ms in 2-ms steps. Each of the seven delays was repeated six times for a total of

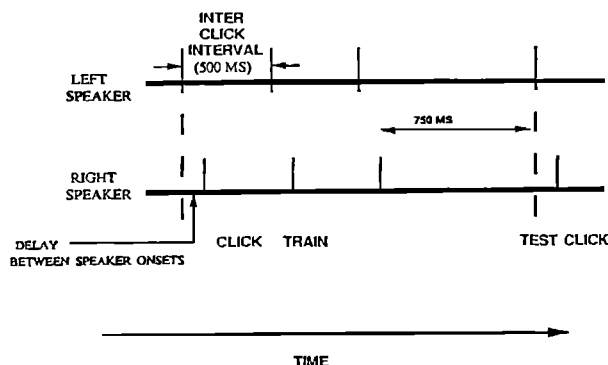


FIG. 1. Schematic representation of test paradigm in experiment 1. In this example, the test click is preceded by 3 click pairs presented at a rate of 2 clicks/s. After the trial, listeners reported whether or not they heard an echo from the vicinity of the right loudspeaker during the test click.

42 trials per block. The intertrial interval, from the subject's response to the subsequent click presentation, was 4 s. The order of trials within a block was random. Each block was repeated three times, so that data points, which reflected the percentage of trials on which an "echo" was reported, were based on 18 trials each.

As shown in Table I, data were obtained for click trains containing 3, 5, 9, and 17 clicks in combination with click rates of 1/s, 2/s, 4/s, 8/s, and 16/s. These number/rate combinations yielded click train durations of 0.5, 1, 2, 4, and 8 s. For example, trains of 2-s duration were produced by 3 clicks at 1/s, 5 clicks at 2/s, 9 clicks at 4/s, and 17 clicks at 8/s. Throughout the rest of this paper, the conditions will be frequently described in terms of the number/rate combination. For example, 9 clicks presented at 4 clicks/s will be denoted R4N9. The 48 trial blocks (16 number/rate combinations \times 3 repetitions per combination) were presented in a random order during the course of 8 to 9 experimental sessions of approximately 1-h duration each.

Results from each of the conditions described above were compared with a baseline condition, termed the NC (no conditioner) condition in which the test click was presented in isolation. Procedures were identical to those used for the click-train conditions. The three NC blocks were presented within 1 week of the 16 click-train conditions.

3. Screening

Because the purpose of this study was to explore the individual and interactive effects of number of clicks, click rate, and train duration on the echo threshold for the test click, only listeners who demonstrated a shift in echo threshold as a result of the preceding click train were of interest. Previous work in this area (Freyman *et al.*, 1989) led us to believe that most, but not necessarily all, listeners would show this type of effect. A brief screening study was conducted in which the NC and R4N9 conditions were compared. The R4N9 condition was selected because pilot work had shown that this conditioning train produced a substantial shift in echo threshold. Procedures were as described above for the main part of the study, except that results for two of the subjects were based on two blocks each, or 12 trials per

TABLE I. Number/rate combinations for click trains used in main study. Values in the body of the table are the corresponding click train durations in seconds.

Rate (clicks/s)	Number of clicks in conditioning train			
	3	5	9	17
1	2	4	8	...
2	1	2	4	8
4	0.5	1	2	4
8	...	0.5	1	2
16	0.5	1

data point, rather than the 18 per point used in the main experiment. Nine young normal-hearing listeners participated. The listeners had pure-tone air-conduction detection thresholds less than or equal to 15 dB HL (*re*: ANSI, 1969) at 0.25, 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, and 8.0 kHz, and had no more than a 10-dB difference between the two ears at any test frequency.

B. Results

1. Screening

Psychometric functions for the screening study are shown for each listener in Fig. 2. For both the NC and R4N9 conditions, the percentage of trials on which an echo was

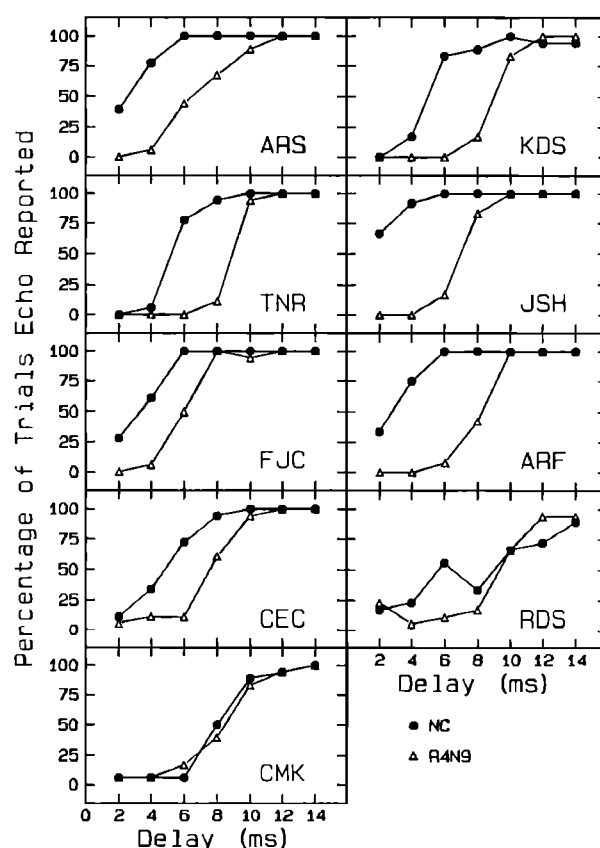


FIG. 2. Results of screening experiment: percentage of trials on which an echo was reported as a function of the delay of the lagging click. Four subjects, ARS, KDS, TNR, and JSH, ran in the remainder of experiment 1.

TABLE II. Echo thresholds in ms and threshold shifts (in parentheses) for the four listeners.

No.	Rate	Dur	Subjects				Mean	s.d.
			ARS	JSH	TNR	KDS		
NC			3.20	4.00	5.50	8.00	5.18	1.83
3	1	2.0	5.18 (1.98)	7.00 (3.00)	7.30 (1.80)	7.59 (-0.41)	6.77 (1.59)	0.94 (1.24)
3	2	1.0	5.47 (2.27)	4.34 (0.34)	8.20 (2.70)	9.27 (1.27)	6.82 (1.65)	1.99 (0.91)
3	4	0.5	2.00 (-1.20)	5.64 (1.64)	6.79 (1.29)	9.36 (1.36)	5.95 (0.77)	2.65 (1.15)
5	1	4.0	7.74 (4.54)	7.37 (3.37)	8.63 (3.13)	9.47 (1.47)	8.30 (3.12)	0.81 (1.10)
5	2	2.0	7.03 (3.83)	6.00 (2.00)	8.20 (2.70)	9.05 (1.05)	7.57 (2.40)	1.16 (1.01)
5	4	1.0	5.63 (2.43)	6.93 (2.93)	7.14 (1.64)	9.67 (1.67)	7.34 (2.17)	1.46 (0.54)
5	8	0.5	6.93 (3.73)	6.77 (2.77)	7.67 (2.17)	11.36 (3.36)	8.18 (3.01)	1.87 (0.59)
9	1	8.0	7.39 (4.19)	7.82 (3.82)	7.82 (2.32)	9.30 (1.30)	8.08 (2.91)	0.72 (1.16)
9	2	4.0	8.00 (4.80)	7.24 (3.24)	8.20 (2.70)	11.42 (3.42)	8.72 (3.54)	1.60 (0.77)
9	4	2.0	8.40 (5.20)	6.00 (2.00)	8.20 (2.70)	10.79 (2.79)	8.35 (3.17)	1.70 (1.21)
9	8	1.0	8.39 (5.19)	8.36 (4.36)	7.41 (1.91)	11.48 (3.48)	8.91 (3.73)	1.54 (1.21)
9	16	0.5	9.07 (5.87)	7.82 (3.82)	8.39 (2.89)	10.79 (2.79)	9.02 (3.84)	1.11 (1.24)
17	2	8.0	8.50 (5.30)	7.80 (3.80)	8.72 (3.22)	11.39 (3.39)	9.10 (3.93)	1.36 (0.82)
17	4	4.0	8.76 (5.56)	7.30 (3.30)	8.72 (3.22)	10.24 (2.24)	8.76 (3.58)	1.04 (1.22)
17	8	2.0	8.79 (5.59)	6.90 (2.90)	8.63 (3.13)	11.16 (3.16)	8.87 (3.70)	1.52 (1.10)
17	16	1.0	9.63 (6.43)	7.10 (3.10)	8.44 (2.94)	10.79 (2.79)	8.99 (3.82)	1.37 (1.51)

reported is plotted as a function of the delay of the lag click. The data for seven of nine listeners demonstrated elevated thresholds in the R4N9 condition relative to the NC condition. The threshold shifts, which ranged from 3–6 ms, indicate that some buildup of echo suppression occurred as a result of the conditioning click train. While it is possible that the other two listeners (CMK and RDS) would have shown this effect with different conditioning train characteristics, only listeners showing a clear threshold shift in this initial session were studied under additional conditions. Four of these seven subjects (ARS, JSH, TNR, and KDS), who were able to participate as listeners for an extended period of time, were actually used for the remainder of the experiment.

2. Number, rate, and duration

The results of this main part of the study were analyzed with the goal of teasing out the individual effects of number of clicks, click rate, and duration of the click train. The most fundamental question is whether the buildup of echo suppression is a function of the duration of the click train or, alternatively, the number of clicks in the train. Echo thresholds (in ms), which were computed by interpolating along the psychometric functions to find the delay corresponding to 50% report of echoes, are displayed for the four listeners in Table II. The numbers in parentheses represent the

threshold shifts produced by the click train. These threshold shifts were computed by subtracting the echo threshold obtained in the NC condition from each echo threshold. The table reveals considerable variability across listeners in the echo threshold in the NC condition, as well as in the size of the threshold shifts. There appears to be a negative relationship across listeners between the echo threshold in the NC condition and the degree of threshold shift. For example, subject ARS had the smallest echo threshold for isolated clicks (3.2 ms), and the largest threshold shifts. Subject KDS had the largest echo threshold in the NC condition (8 ms), but relatively small threshold shifts. It is not known from this small sample whether such a trend would be observed in a large population of subjects.

Figures 3 and 4 display the mean echo threshold shifts for the 16 conditions plotted as a function of the number of clicks. Standard deviations of each data point across listeners are available in the rightmost column of Table II. Figure 3 demonstrates that, for fixed train durations, the echo threshold shift increased with increasing number of clicks in the train, especially over the range from 3–9 clicks. The change in threshold was more gradual between 9 and 17 clicks, suggesting that the functions may have been approaching an asymptote. For each number condition, the effect of duration appeared to be small and nonsystematic. Thus these results are consistent with data obtained in a dif-

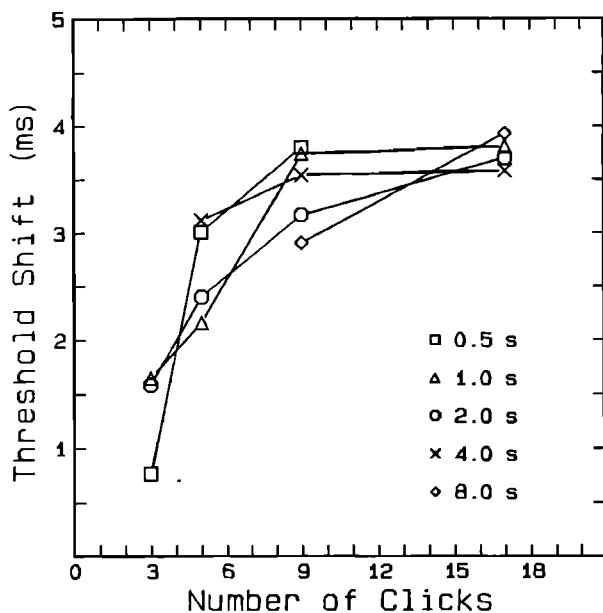


FIG. 3. Effect of number of clicks in the conditioning train on the echo threshold shift relative to the NC condition. Lines connect data points representing equal train durations.

ferent paradigm (Clifton and Freyman, 1989) in that the shift in echo threshold was dependent on the *number* of clicks in a preceding train rather than on the duration of the train.

When either duration or number of clicks is varied for fixed values of the other variable, the click rate changes as well. However, the influence of rate is difficult to extract from Fig. 3. Figure 4 replots the threshold shifts as a function of the number of clicks, but this time with lines connect-

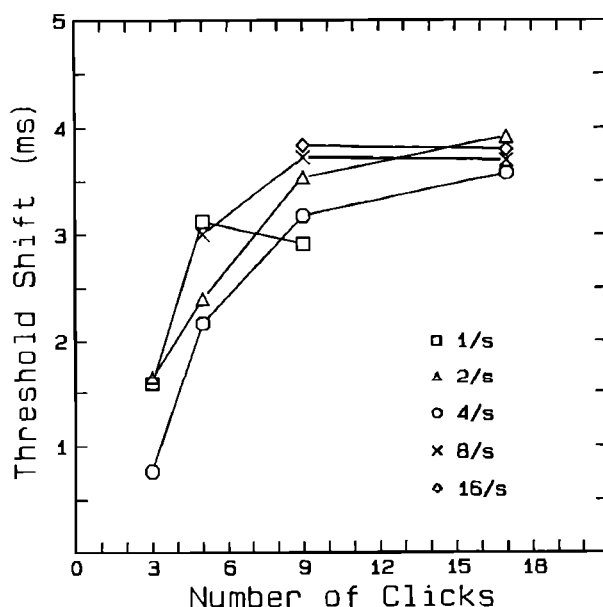


FIG. 4. Effect of number of clicks in the conditioning train on the echo threshold shift relative to the NC condition. Lines connect data points representing equal click rates.

ing equal click rates. The figure again shows a substantial effect of number of clicks, while little systematic effect of click rate is observed. Taken together, Figs. 3 and 4 indicate that the shift in echo threshold is directly influenced by the number of clicks in the preceding train. Independent of the number of clicks, neither the duration of the train nor the click rate appear to have a systematic influence on echo threshold over the range of conditions tested.

3. Fast click rates

Thurlow and Parks (1961) reported that the echo threshold for clicks increased when the click rate was increased from 1/s to 5/s but decreased again when the click rate was increased to 50/s. They did not specify the time interval during the click train on which listeners based their judgments. However, the current data on number of clicks suggest that if there was a buildup of suppression at the 50 clicks/s rate, it would occur in the first few hundred milliseconds. Thus their finding of low echo thresholds for the 50/s rate led us to suspect that the buildup of suppression may not occur at fast rates.

Additional conditions were run to determine whether a click train with a 50/s rate produces a buildup of echo suppression in the same way as conditioning trains with slower click rates. The same four subjects participated. The procedures were essentially the same as those used for the main set of conditions, except that the conditioning train consisted of 25 clicks presented at either 16 or 50 clicks/s. Delays were 2, 4, 6, and 8 ms, rather than the 2–14 ms that had been used above. The interclick interval at the 50/s rate is only 20 ms, and delays of 10 ms or greater, which are half or more of that interval, may produce ambiguities about what is the lead and what is the lag. To avoid possible range effects influencing the comparison with the NC condition, the isolated click condition was rerun using delays of 2, 4, 6, and 8 ms, instead of extracting those delays from the 2- to 14-ms data.

The individual and mean psychometric functions for the fast click rate condition are displayed in Fig. 5. Several of the functions were truncated by the absence of data points above 8 ms. However, the buildup of suppression is clear. In comparison with the test click in isolation, both conditions with the preceding click train resulted in a decrease in the percentage of trials on which the echo was reported. The average data revealed only small differences between the results at 16 and 50 ms. Thus these data suggest that even very brief click trains with extremely fast rates produce a buildup of echo suppression.

II. EXPERIMENT 2: WHITE NOISE STIMULI

While experiment 1 indicated that number of clicks was an important determiner of the buildup of echo suppression, this effect may depend on a continual train of identical events. If this were true, a train of nonidentical clicks differing from one another and the final test click should produce no buildup. If it were the case that buildup depended upon identical tokens throughout train and test stimuli, this would preclude further experiments manipulating physical differences between train and test stimuli (e.g., as in experiment 3). In experiment 2, echo threshold for a test noise

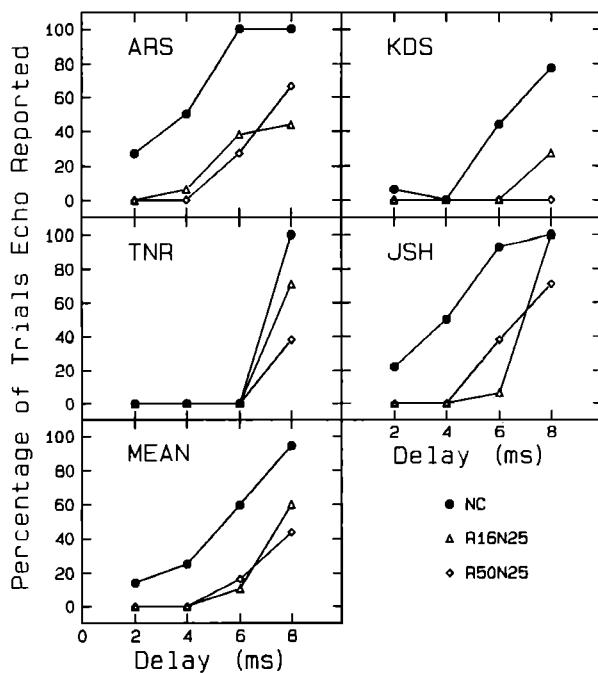


FIG. 5. Individual and averaged data comparing R50N25 with R16N25 and NC. In each panel, the percentage of trials on which an echo was reported is plotted as a function of the delay of the lagging click on the test click.

burst preceded by a train of random noise bursts was compared to threshold preceded by repetitions of a single noise burst.

A. Method

The stimuli presented during both the “click train” and “test click” were 4-ms bursts of computer-generated white noise shaped with a 2-ms linear rise/fall time. Three conditions were presented: (1) R4N9 with single-token “frozen” noise, in which a single token of noise was repeated during the conditioning train and test burst. However, a different token of noise was used for each trial. The R4N9 train was used because experiment 1 revealed a large effect of 9 clicks, with little additional increase in echo threshold at 17 clicks. A rate of 4 bursts/s was chosen to create a relatively short train of 2-s duration; (2) R4N9 with multiple noise tokens, in which each token in the train, as well as the test burst, was randomly selected from a long segment of white noise; and (3) NC, where the test burst was presented in isolation. For all three conditions, the noise tokens delivered from the left and right loudspeakers were always identical, except for a delay to the right loudspeaker. The stimuli were delivered at a level of approximately 53 dBA. The period of silence between the end of the noise train and test burst was 750 ms as before. The lag delays were 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, and 33 ms, distributed randomly through blocks of 44 trials in which each delay condition was revisited four times. Four blocks were run for each condition for a total of 16 trials per delay. Four young normal-hearing listeners participated, two of whom (ARS and JSH) had participated in the previous experiment. Testing procedures and instruc-

tions for subjects were identical to those used in the click studies.

B. Results

Echo thresholds for the three conditions are shown for the group and for each subject separately in Fig. 6. Two trends are clear. First, a train of noise bursts presented before the test burst produced a shift in echo threshold relative to the NC condition, regardless of whether the train contained identical or randomly varying noise bursts. The average threshold for the noise-train conditions was 10.8 ms, compared with 6.37 ms for the isolated test click (NC) condition. Second, the threshold shifts for the multiple-token R4N9 condition were at least as large as those for the single-token condition. The average thresholds were 11.51 and 10.15 ms, respectively. Thus echo suppression built up during the conditioning train, even though the stimuli in the train were not identical to one another. This finding may be specific to the case of independent samples from the same white noise. That is, it cannot necessarily be assumed that echo threshold shifts would be produced by trains consisting of noise bursts of different narrow-band frequencies, levels, etc. However, the fact that the noise bursts in the train do not need to be identical suggests that echo suppression does not rest upon the repetition of the same sound throughout the trial.

III. EXPERIMENT 3: PRESENCE OF LEAD AND LAG SIGNALS

Experiment 3 investigated whether it is necessary for the echo click to be present during the click train. Must stimuli be presented from both the lead and lag loudspeakers during the conditioning train in order to produce a shift in echo threshold? The purpose of experiment 3 was to begin to address the issue of precisely what produces the change in echo suppression. Is the mere presence of a click train sufficient to produce echo threshold changes, or must the train contain

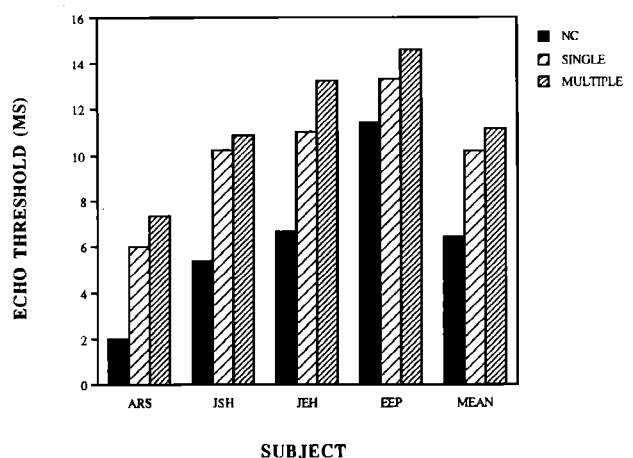


FIG. 6. Individual and averaged echo thresholds for 4-ms bursts of white noise. The NC condition is compared with two R4N9 conditions: “single” token, in which the nine bursts during the train were identical to each other and to the test burst on each trial, and “multiple” token, in which the conditioning train and test bursts were independent samples of noise.

an echo click? Four experimental conditions were run using the 4-ms multiple-token white noise stimuli to address these issues: (1) R4N9 with only the lead (left) loudspeaker active during the conditioning train, but with stimuli presented from both loudspeakers during the test burst (the "LE" condition); (2) R4N9 with noise presentations from only the lag (right) loudspeaker during the conditioning train (the "LG" condition); (3) R4N9 with both lead and lag presented during the train (the "PE" condition), which was similar to the multiple-token noise condition used in the previous experiment; and (4) NC, where the test noise burst was presented in isolation.

The LE and LG conditions were considerably different from any of the conditions run previously in this study, in that only one loudspeaker was active during the conditioning train. The perceptual experience during the train is that of a softer, thinner, more compact image coming from one loudspeaker. When both lead and lag signals are then presented during the test burst which follows the train, the image is louder and more diffuse. We were concerned that subjects, faced with these qualitatively different stimuli, would have difficulty maintaining a constant criterion for reporting the presence or absence of echoes across the four conditions. To circumvent this potential criterion problem, subjects chose which of two loudspeakers emitted the echo on the test burst, instead of reporting whether or not they heard an echo. We reasoned that subjects' performance on the new task should be correlated with the subjective echo threshold. That is, the discrimination between loudspeaker locations should be difficult at delays below echo threshold and should improve dramatically as delay is increased to the point where the lag click is clearly audible and can thus be localized.

A. Method

The apparatus for the objective experiment was identical to the previous one, except that two additional matched Minimus 7 loudspeakers were placed 10 deg on either side of the lag loudspeaker. Thus the full configuration consisted of one lead loudspeaker at 45 deg left of midline and three lag loudspeakers situated at 35, 45, and 55 deg to the right of midline. For the LE condition, the signal during the conditioning train was presented only from the lead loudspeaker, and for the LG condition, only from the center (45 deg) lag loudspeaker. For the PE condition, the signal during the train was presented from both the lead and the center lag loudspeaker. During the test noise, the lead signal was always presented from the left loudspeaker. The lag signal was presented from either the leftmost (35 deg) or rightmost (55 deg) lag loudspeaker. The subjects' task was to report, by pressing the appropriate button on a response panel, whether the lag sound originated from the left or right lag loudspeaker. Correct-answer feedback was provided on every trial.

The method of constant stimuli was used to evaluate subject performance as a function of the delay of the lagging noise. The delays were 3, 6, 9, 12, and 15 ms for the LE, LG, and NC conditions, and were 9, 12, 15, 18, and 21 ms for the PE condition. One subject (RYL) had a higher threshold on

the NC condition and delays were extended to 18 ms. Stimuli were delivered in blocks of 20 trials, with delay fixed within a block. The lag noise originated from left lag loudspeaker for ten of the trials and from the right for the other ten. The left and right presentations were distributed randomly through each block. All five blocks (one for each delay) for each condition were presented in a random order before a new condition was begun. The order of conditions was also randomized. Once all four conditions had been completed, the process was repeated twice more (with new random orders) so that the total data set for each subject consisted of 60 trials at each of five delays for all four conditions.

In addition to the four objective conditions, subjects also obtained a subjective echo threshold for the NC condition to facilitate comparisons between subjective and objective results. The subjective methodology was identical to that described for experiment 2, except that only the seven delays from 3–21 ms were used. Three blocks of 42 trials each (7 delays \times 6 repetitions of each delay) yielded 18 trials per data point.

Four subjects participated who met the criteria for normal hearing stated previously. One (CEC) had participated in the screening portion of experiment 1; the other three (the authors) had not participated in any previous studies reported here. However, all three had considerable experience listening in the anechoic chamber. All subjects were given at least 2 h of practice with the specific discrimination task before data collection was begun.

B. Results

The results of experiment 3 are displayed in Figs. 7 and 8. Figure 7 is a comparison between the subjective and objec-

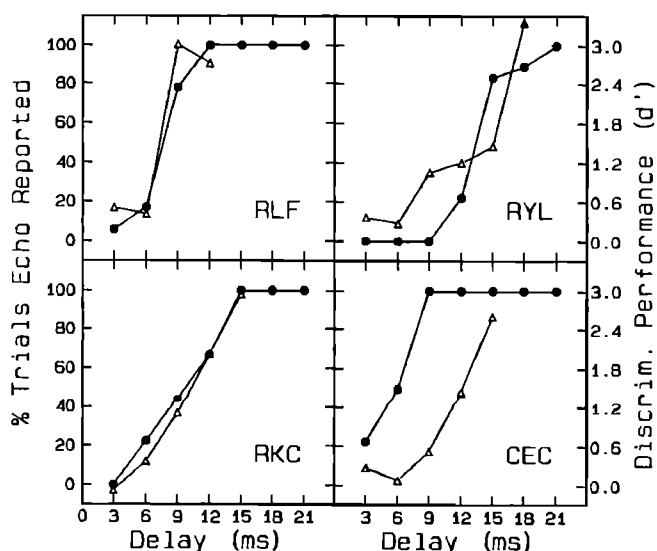


FIG. 7. Comparison between subjective and objective psychometric functions for 4-ms bursts of white noise in the NC condition. The subjective data (closed circles) are the percentage of trials on which an echo was reported. The objective data (open triangles) represent discrimination performance in d' for two lag loudspeakers separated by 20 deg.

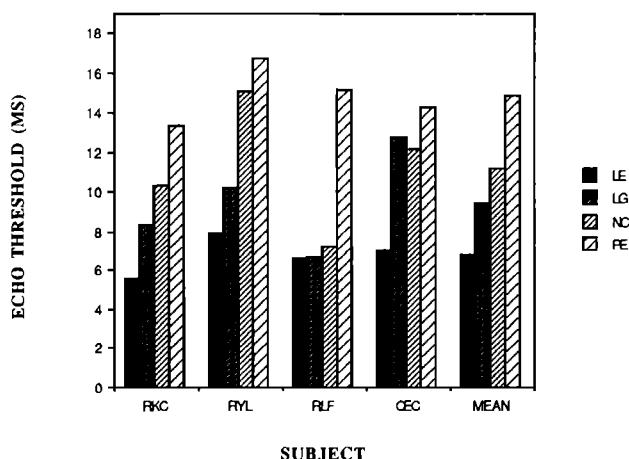


FIG. 8. Delay required for a d' of 1.5 on the lag loudspeaker discrimination task. "LE" is R4N9 with only the lead loudspeaker active during the conditioning train. "LG" is R4N9 with only the center lag loudspeaker active during the train. "PE" is R4N9 with both lead and lag presented during the train. "NC" is no conditioning train.

tive results for the NC condition. The ordinate was scaled so that 50% echoes reported on the subjective task corresponds to a d' of 1.5 on the objective task. The subjective and objective functions are very well matched for RKC and RLF, and are reasonably similar for RYL. Thus, for the three more experienced subjects, the discrimination task presented little difficulty as long as the lag click was audible as a separate event. However, this does not appear to have been true for CEC, whose objective function is shifted by approximately 6 ms relative to the subjective results. An additional possibility is that she adopted a relatively lax criterion for reporting the presence of an echo during the subjective task, or based her judgment on whether or not the lag sound influenced the localization of the lead sound to a perceptible degree. Either strategy would have shifted the subjective function to the left. All subjects had difficulty with the discrimination task when the lag click was subjectively inaudible. Although all four listeners reported that they were occasionally able to attend to subtle cues in the fused sound localized to the left that seemed to reveal which lag loudspeaker was active, these cues were apparently unreliable. Thus the data suggest that even after several hours of practice with feedback, good performance on the discrimination task required that the lag click be heard as a separate sound.

Figure 8 displays echo thresholds for the four discrimination conditions. The thresholds were derived from the psychometric functions by interpolating to find the delay corresponding to a d' of 1.5. The average data, displayed on the right, indicate that the LE condition produced the lowest thresholds (6.81 ms), followed by LG (9.44 ms), NC (11.19 ms), and PE (14.87 ms). Among the individual subjects, both RKC and RYL demonstrated trends typical of the average data. Subject CEC's data were similar to the average results except for the similarity of the NC and LG conditions. RLF demonstrated minimal differences between any of the conditions with the exception of his much higher threshold for the PE condition.

The fact that the PE threshold was higher than the NC

threshold for every subject indicates that the buildup of echo suppression during a stimulus train, observed previously with the subjective task, is also measurable with the discrimination paradigm. Thus a train of nine noise bursts presented at a rate of 4 bursts/s interferes with the ability to hear and localize echoes. The most striking result is the difference of about 8 ms in mean thresholds between the LE and PE conditions. The two conditions are identical except that, in the PE condition, both lead and lag are presented during the conditioning train, whereas, in the LE condition, only the lead sound is presented. The difference demonstrates clearly that the lag sound must be present during the train in order to produce a buildup in suppression. The fact that thresholds were also lower in the LG condition than the PE condition indicates that a train of bursts may come from the location where the lagging sound will be on the test burst, and this does not raise echo threshold compared to the isolated test noise. Both lead and lag must be present during the conditioning train to produce a buildup of suppression.

Not only was there no buildup of echo suppression during the single-source trains, but, to the contrary, single-source trains appeared to *enhance* discrimination performance, particularly for the LE condition. For three of the four observers, thresholds were considerably lower in the LE condition than in the NC condition. That is, relative to the test burst in isolation, these subjects were more easily able to identify the lag loudspeaker location when the test burst was preceded by a train of single-source bursts from the lead side. Subjects reported that the echo seemed to "pop out" after the single-source train. The use of the discrimination experiment as opposed to the subjective paradigm insured that the apparent enhancement of the echo was not simply caused by a shift in criterion produced by the single-source train.

IV. GENERAL DISCUSSION

The results of these experiments indicate that the strength of echo suppression, as defined by the echo threshold, changes as a function of ongoing auditory stimulation. In experiment 1 it was shown that for the majority of listeners, a brief train of identical click pairs presented just prior to a test click tends to increase the echo threshold for the test click, i.e., decrease the localization of an echo at a given delay. The amount of threshold shift is influenced by the number of clicks in the train; for a fixed number of clicks, the threshold shift appears to be independent of the duration of the conditioning click train and of click rate between 1 and 50 clicks/s. We interpret these results as indicating that echo suppression builds up during a click train; the suppression extends through the interruption between the click train and test click and is measurable as an increased echo threshold for the test click.

The current results clarify interpretations of our previous work on dynamic aspects of the precedence effect. Those studies (Clifton, 1987; Clifton and Freyman, 1989) demonstrated that echo threshold was lowered immediately following a sudden switch in location of lead and lag clicks, but as the click train progressed in the new locations the echo became inaudible. The data suggested that the number of clicks in the train determined the extent of this fade out.

However, because the duration of the train was held constant (12 s), the effect of number of clicks could not be clearly separated from click rate. With a different methodology, the current study quantified the echo's fade out more accurately and over a wider range of conditions than the previous work, and confirmed the importance of the number of clicks presented during the train in determining the echo threshold.

The importance of the number of stimulus repetitions during the train suggests that information from each click is being extracted which leads to echo suppression. The switch paradigm breaks the effect of repetition by introducing a new set of stimuli to be attended to; echo suppression is momentarily relaxed until more information (i.e., more clicks) is received and suppression is re-established. Recent results suggest that the switch event itself becomes less effective with repetition. Blauert and Col (1989) reported that if lead and lag locations are switched repeatedly, the listener's echo threshold stabilized when the switch occurred regularly, but if switching was done irregularly, the breakdown in echo threshold continued to occur after the switch. Blauert and Col (1989) recognized this as evidence for a cognitive role in the precedence effect. In this case, the switch itself is seen as information to be incorporated into the decision-making process of echo suppression. Repetition of the switch provides the redundancy needed to maintain echo suppression across the switch in location of lead and lag stimuli.

Our results showing little systematic effect of click rate through 50 clicks/s seem on the surface to be inconsistent with the findings of Thurlow and Parks (1961). They reported that echo thresholds were higher for a 5/s rate than a 1/s rate, but decreased again at 50/s. The discrepancy in results as a function of rate could be explained by the different methodologies. The subjects in Thurlow and Parks's study reported on their perceptions *during* a click train, while our subjects based their responses on an isolated click presented *after* the train. Thurlow and Parks did not report the time interval during a click train when listeners were asked to make their judgment. However, our results concerning the effect of number of clicks on echo perceptibility suggest that echo perception may have been shifting more quickly at the faster click rates. Relative to the 1/s rate, echo suppression at the 5/s rate would have built up more quickly, and could have been responsible for the higher echo threshold. Theoretically, the same reasoning should apply to the 50/s rate, yet they found that echo threshold dropped relative to the 5/s rate. One possible explanation is the fact that, at the 50/s rate, the interval between successive lead clicks is only 20 ms. Therefore, each lag click is presented only a few ms before the following lead click. It may be difficult for the nervous system to sort out the original sound from the echo, and the strength of echo suppression could be affected by this ambiguity. As our subjects were instructed not to base their judgments on their perceptions during the train, these potential ambiguities would be expected to have less influence in our experiments than in theirs.¹

Experiment 2 demonstrated that shifts in echo threshold could be produced by trains of white noise bursts, regardless of whether the bursts were repetitions of the same token

of noise or were independent samples of noise. This latter finding is important for both practical and theoretical reasons. From a practical standpoint, independent samples of noise produce variations in sound quality within the train and test click. This is methodologically important for discrimination paradigms such as experiment 3, where the use of clicks or single noise tokens may have allowed subjects to distinguish the lag loudspeaker location based on idiosyncratic differences in sound quality in a two-choice situation. The variation produced by multiple tokens increased the likelihood that subjects were forced to attend to changes in the perceived location of the sound rather than changes in quality. From a theoretical viewpoint, we can conclude that increases in echo suppression during the conditioning train are not affected by variations in the ongoing sound. The typical listening situation in everyday environments is one in which sounds from a source vary acoustically from moment to moment. An echo suppression mechanism should ignore such variations as they do not indicate a change in the sound's source or its associated echoes. The random variation in the noise bursts during the train would not be expected to disrupt the buildup in echo suppression.

In experiment 3 echo thresholds were higher when both leading and lagging sounds were presented during the train than when either lead or lag alone was presented. The listener must receive input from both lead and lag loudspeakers in order to increase echo suppression. These results comparing two-source and single-source conditioning trains seem to resolve contradictions between our earlier work and the results presented by Wolf (1988). For several fixed lag-click delays, Wolf measured the level of the lag click required for subjects to report hearing an echo. Relative to the test noise in isolation, threshold levels were substantially lower when the test click was preceded by a single-source click train coming from the lead side (similar to our LE condition). That is, the click train enhanced the audibility of the echo. These results initially seemed to conflict with our basic finding of echo suppression increasing in strength during a click train. However, experiment 3 in the current study revealed the critical difference, i.e., that the buildup requires both lead and lag clicks to be present during the click train. Our results for the LE condition replicated those obtained by Wolf quite well, in that echo perceptibility was apparently enhanced by a train of single-source noise bursts from the lead side. However, the effect was the opposite (echo perceptibility was degraded) in the PE condition where both the lead and lag sounds were presented during the train.

The data from the LE condition in experiment 3 help explicate a recent result of Perrott *et al.* (1989), in which a weak precedence effect was reported. These authors tested listeners' MAA under precedence-effect conditions and single-source conditions, and found only a slight elevation in MAA threshold for the former. For the precedence effect condition a center loudspeaker at 0 deg azimuth always emitted the lead sound, with two flanking lag loudspeakers which could be moved to create different angular distances from the lead. Listeners were able to discriminate the correct lagging loudspeaker at angles of around 3 to 4 deg, with delays between 2 and 5 ms. Perrott *et al.*'s procedure had two

features that would be expected to enhance the influence of the lag. One, they delivered a single 5-ms test noise burst on each trial that was not preceded by a train of bursts. Two, immediately before the test noise burst, the center loudspeaker alone emitted a burst to serve as a reference point, but also offered listeners a contrast like our LE condition, which had the lowest echo threshold of the four conditions. It is not clear why the contrast of a single source sound followed immediately by a lead-lag pair should enhance the echo's influence. Most likely the enhancement is due to a perceptual contrast effect. Wolf (1988) manipulated a number of single source clicks in the preceding train and found that as the number increased from 1 to 8, the echo on the test click was heard more easily, although the effect was not linear. If Perrott *et al.*'s finding of a weak precedence effect does reflect perceptual contrast, this would confirm that even a single token has an effect.

The fact that both lead and lag sounds are required to produce the buildup allows us to begin to postulate possible mechanisms underlying the buildup of echo suppression. The nervous system evaluates information from two different sources, and if the delay between them is long enough (above the echo threshold for the NC condition), the second sound is heard as a separate auditory event. However, as the two sounds are repeated several times, the nervous system begins to recognize that the second sound is a reflection of the first, and attempts to suppress it. As each new pair of sounds is presented, the suppression increases in progressively smaller increments until the effect saturates. Our results suggest that lag sounds with delays as much as 6 or 8 ms above echo threshold can sometimes be suppressed by a stimulus train of nine noise bursts (see the difference between RLF's NC and PE results in Fig. 8). Even very brief click trains at rapid rates increase echo threshold. Rapidly pulsed stimuli convey much information to the auditory system in a brief time interval. If some minimum amount of information is necessary in order for a delayed signal to be recognized as an echo, complex signals will transmit this minimum information so rapidly that listeners will be unaware of the echo threshold shifts. Only when brief bits of information are spread out over several seconds, as in a slow click train, will the listener be aware of the initial location of echoes followed by their fading away after a few repetitions.

Our research has not yet answered questions about how specific the buildup of echo suppression is to the frequency, intensity, direction, or delay of the conditioning lag sound. Perhaps the most interesting issue is the size of the spatial area that is suppressed. In experiment 3, the lag stimulus during the test click was 10 deg to the right or left of the lag signal during the conditioning train, and the suppression was still effective. However, if the lag test stimulus was moved further from the conditioner's location, the increased suppression could break down. The effect might also break down if the lag click delay during the test click was different from the conditioning train, which would simulate a shift in the distance of a reflecting surface. Answers to these questions should assist in the theoretical interpretation of the buildup of echo suppression and improve our understanding of its practical importance in real listening environments.

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¹ In piloting the 50/s rate, perceptual changes during the click train were most obvious to the experimenters when the lag-click delay was at least 10 ms, half or more of the 20-ms interclick interval. For example, while listening at a lag-click delay of 12 ms, the experimenters perceived the stimulus direction shifting from left ("leading" side) to right ("lagging" side) soon after the onset of the train. This suggests that as the click train progressed, the right loudspeaker was treated as the lead, with an 8-ms delay to the left loudspeaker. The fact that the left loudspeaker was the lead for the very first stimulus was eventually ignored. Additional pilot testing revealed that the perceptual switch took place within the first few click presentations. Further experimentation with these conditions might prove useful for studying the relative contributions of onset versus ongoing information in sound localization.

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