What the precedence effect tells us about room acoustics

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Sound produced in a room is typically followed by numerous reflected sounds from nearby surfaces; yet we perceive a single sound source. This perceptual phenomenon, known as the precedence effect, has long been assumed to involve echo suppression, but the nature of this suppression remains unclear. In two experiments, we investigated whether information about the lagging sound's location was perceived. Our hypothesis was that such information is critical because reflected sound can function to inform the listener about objects and structures in the room. Listeners reported hearing more echoes under a stimulus situation that simulated sudden, unexpected changes in the location of the lagging sounds, as compared with stable stimulus conditions. Placement of lagging sounds' locations proved to be critical in that a sudden shift per se did not disrupt the fusion aspect of the precedence effect; the new location had to occupy a site that specified a new reflecting surface. Perception of echoes appears to be modulated by room acoustic information contained in reflected sound and listeners' expectations about this.

When we listen to sound, unless that sound is made in an anechoic environment, it is always accompanied by reflected sound from walls, ceiling, floor, and objects in the room. If the delay between the original sound and the reflections is sufficiently long, the lagging sounds are heard as echoes. Echo threshold is defined as the time delay below which delayed sounds are not heard as separate sources at locations apart from the original sound (Blauert, 1997, p. 224). In effect, the reflections or lagging sounds are fused with the original or leading sound to yield the percept of a single source. This perceptual illusion is the fusion aspect of the precedence effect and has traditionally been described in terms of echo suppression (Green, 1976, pp. 216–218; Mills, 1972). Even when not heard as a separate auditory event, lagging sounds influence the global auditory percept. Rich information about the surround is contained in “unheard” echoes below echo threshold. Reflected sound contains information about the presence, azimuthal location, and distance of a reflecting surface, with reference to the listener. This report is concerned with listeners' sensitivity to the directional location of delayed sound.

A startling example of how echo suppression can change from one moment to the next is found in the Clifton effect (Clifton, 1987). The experimental setup is a click

train, composed of a leading click from the left and a lagging click from the right (or vice versa) and presented at a delay below echo threshold, so that the listener perceives the leading click to be localized as the sole source of sound at its location. When the leading and the lagging click sides are suddenly reversed, echo threshold is lowered so that both clicks are heard and localized at their respective locations. If the reversed train continues, after a few clicks in the new positions, echo suppression is re-established, so that a fused image is localized at the leading click's location. This transition from hearing leading and lagging clicks on both sides to a fused click on the leading side can also be observed at the very start of a click train. In effect, echo threshold is raised by the continuation of the click and its accompanying reflections. The number of clicks in the train steadily increases echo threshold up to around nine clicks, after which the effect levels off (Freyman, Clifton, & Litovsky, 1991). We have called this changing perception a *build up* in echo suppression and have attributed it to the listener's experience with the ongoing click train (Clifton & Freyman, 1997).

An interesting variation of the Clifton effect was performed by Blauert and Col (1992). When the switch of location was repeated so that the side of leading and lagging clicks alternated, listeners first heard both the lead and the lag sounds following each switch, but after several repetitions they heard only the lead sound jumping back and forth. The effect was gradual; as the subjects experienced the switch repeatedly, the time taken to achieve fusion and suppress the echo shortened. An important control for the Clifton effect was performed by Yost and Guzman (1996). They showed that simply moving the location of leading and lagging sounds did *not* produce the Clifton effect. They positioned lead and lag

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clicks on opposite sides during the train, then shifted their locations laterally while leaving them on the same side for the test click. Echo threshold was not affected, so apparently lead and lag must trade sides to produce the effect.

We have interpreted both the buildup and the breakdown phenomena as supporting a model of the precedence effect as an active perceptual process that depends in part on the listener's expectations (Clifton, Freyman, Litovsky, & McCall, 1994). These expectations arise from hearing sound produced in a particular location and are based on information from both the original sound and the accompanying reflections. Reflected sound informs the listener about the acoustics of the surroundings, an idea first expressed by Benade (1976, pp. 197–210). The precedence effect is seen as a dynamic process, subject to moment-to-moment changes, rather than as a mechanistic, hard-wired part of the nervous system. Clifton et al. (1994) made a specific hypothesis about how the precedence effect is related to room acoustics: "Changes in echoes from the reflecting surfaces that are apt to be experienced in everyday life will not disrupt echo suppression, but changes that are improbable will disrupt the process." From this hypothesis, the prediction was made that "Echo threshold should be lower when changes in the ongoing echo signify either new properties of reflective surfaces in the room or unusual movement of these surfaces" (p. 1532). In the case of the Clifton effect, the room acoustics hypothesis predicts a lowering of echo threshold because before the switch in locations there was no reflecting surface on the leading side but after the switch a lagging sound was suddenly present from that side; thus, it became an audible echo owing to its unexpected nature. Continued echoes from that location led to suppression as this new information became incorporated. Similarly, when Blauert and Col (1992) alternated sides for leading and lagging sounds repeatedly, eventually even this rather unnatural arrangement became accepted, and perception of the echo was blocked. These results suggest that our expectations about room acoustics are highly malleable. They are quickly formed, can be quickly disrupted, and can be quickly reformed as new information continues to arrive. And why not? We do not live in static acoustic environments, and we should be able to adjust to changing circumstances.

The present experiments put the room acoustics hypothesis to an acid test by trying to make the Clifton effect disappear. In the first experiment, two lagging sounds were introduced at the start of a train of noise bursts, Lag A on the left side and Lag B on the right side, where the leading burst was also located. At the switch, Lag A and the leading burst switched sides, so that the lead was now on the left and the previously left lag was on the right, in the lead's old position. We predicted that the Clifton effect would disappear because there was no new (unexpected) information about reflected sound in the environment. Before the switch, there was a lag sound (Lag B)

on the lead side, and when the lead switched over, a lagging sound was still on that side. No new reflecting surface appeared to change the room acoustics. This condition was compared with two control conditions: the "classic" switch of a single lead and a single lag switching positions and no switch of lead and lag after the train. The two-lag switch condition should yield data much like the no-switch condition. The second experiment examines whether the location of the second lag is critical.

EXPERIMENT 1

Method

Subjects. Twenty-four undergraduate students participated. Three students displayed a mild hearing loss (thresholds of 30–35 dB at 6 kHz), and their data were not included in the analyses, leaving 21 subjects who had normal audiograms (<20 dB HL at 0.25, 0.5, 1, 2, 3, 4, and 6 kHz).

Stimuli and Apparatus. The stimuli were 4-msec white noise bursts, including 1-msec rise/fall times, and were presented via a D/A converter at 20 kHz and low-pass filtered at 8.5 kHz, with a cutoff frequency of 8.5 kHz. Noise bursts were presented in lead/lag pairs, with delays ranging between 2 and 14 msec in 2-msec steps. The same sample of noise was used within a pair, with different samples used across pairs.

The subject sat in a chair at the center of an anechoic chamber ($4.9 \times 4.1 \times 3.1$ m), whose floor, ceiling, and walls were covered with 0.72-m foam wedges. Two loudspeakers were positioned in a semicircle array at 45° left and right of midline and a third at 55° right, with all sources at a distance of 1.9 m from the subject's head. The center of the loudspeakers was 1.04 m above the wire mesh floor of the chamber, the approximate height of the typical subject's ears while seated in the chair. Stimulus level was measured using a microphone placed at the position of the center of the subject's head and by presenting trains of noise bursts at 8/sec. Stimulus level, measured with an SLM (B&K Type 2204) set on the "fast" meter response, was 41 dBC.

Procedure. Three conditions were presented in which a train of 17 noise burst pairs was followed by a test burst pair; the train was presented at a rate of 8 bursts/sec with a pause of 750 msec between the train and the test burst pairs. The subjects were instructed to judge whether or not they heard an echo, defined as a sound coming from the vicinity of the right loudspeakers, on the test burst pair. The test burst pair was exactly the same in all conditions and featured the leading burst at 45° left and the lagging burst at 45° right. The three conditions manipulated the position of the lagging stimuli available during the train in order to determine their effect on perception of the test burst pair (see Table 1 for the location of all

Table 1
Stimulus Conditions for Experiment 1

Condition	Train	Test
No switch (buildup)	lead 45° left lag 45° right	lead 45° left lag 45° right
Classic switch (one echo)	lead 45° right lag 45° left	lead 45° left lag 45° right
Two lags	lead 45° right Lag A 45° left Lag B 55° right	lead 45° left lag 45° right
No train (baseline)		lead 45° left lag 45° right

ANECHOIC CHAMBER

Figure 1. A schematic diagram of loudspeaker arrangements in Experiments 1 and 2. The opaque loudspeaker symbols were used in Experiment 1; all four symbols, including the shaded symbol, were used in Experiment 2.

the loudspeakers during train and test and Figure 1 for a schematic diagram of the loudspeaker arrangement in the anechoic chamber). In the two-lags condition, the leading burst was located at 45° right during the train, with Lagging Sound A at 45° left and Lagging Sound B at 55° right. For the test burst, the leading and lagging stimuli that were previously at 45° switched positions, and Lag B was turned off. The one-lag, or classic, switch condition was the same as the two-lags condition, except that there was no second lag at 55° right during the train. The no-switch condition had the leading burst at 45° left and the lagging burst at 45° right—that is, the same configuration as for the test burst, so that there was no change in location between train and test bursts. This condition measures the increased difficulty in hearing an echo that occurs owing to repetition of a sound source and associated reflections in a room. As such, it is the standard against which to measure the effect of switching the sides of the source and the lag in the two previous conditions. A final control condition (no train) consisted of the test burst not preceded by a train. This control sets the baseline for hearing an echo independent of the possible effects of the preceding train.

There were seven delays (2–14 msec) between the leading and the lagging noise bursts in the three control conditions that had single echoes. In the two-lags condition during the train, the first lagging stimulus (Lag A) also varied between 2 and 14 msec, whereas the second lagging stimulus (Lag B) was double that for Lag A in relation to lead onset. For example, if Lag A was 2 msec, Lag B was 4 msec, or if Lag A was 14 msec, Lag B was 28 msec. Delays remained constant throughout the train on a trial, and the delay during the test burst was always the same as the delay during the train for single-echo conditions and for Lag A in the two-echoes condition. Thus, delays for test bursts during all the conditions varied between 2 and 14 msec. Within each condition, each of the seven delays was presented seven times, for a total of 49 trials in a block per condition. The presentation of delays within a condition block was random for each subject. Each condition block was run twice for each subject, for a total of 14 trials at each delay. The four conditions were run in four different orders so that, across subjects, each

condition appeared in each ordinal position. The subjects were randomly assigned to a particular order of conditions.

The subjects were given practice runs of seven trials, one at each delay, for each condition. They were instructed to press a button under a green light if they heard an echo or to press the button under the red light if they did not hear an echo on the test burst. Throughout the session, the subjects controlled the rate of stimulus presentation. An indefinite amount of time was allowed for the subject's response after a test burst ended; however, the subjects usually responded within 2–3 sec after the test burst. Once a choice from the button box had been made, the next train of clicks was presented immediately.

Results and Discussion

The number of trials on which each subject reported an echo on the test burst was summed for each delay within each condition. The percentage of trials on which an echo was reported averaged over all the subjects is shown in Figure 2. Each datapoint in the figure is based on 294 responses (21 subjects $\times$ 14 trials). The no-train condition is a baseline against which to judge the effect of the train. Listeners reported echoes on about 45% of the trials at the shortest delay, and this increased to 70% at 14 msec. The effect of the repeating train on echo threshold is seen in the no-switch condition, in which the test burst is delivered in the same location as during the train. Here, listeners reported fewer echoes, as compared with the no-train condition, at all delays, with the greatest difference being at the shorter delays (2–8 msec), at which 20% or fewer echo responses were reported. On the other hand, the effectiveness of the train in suppressing echoes can be undone by exchanging the locations of the leading and the lagging sounds on the test burst. Performance in the clas-

Table 2
Comparisons at Each Delay (in Milliseconds)
Among Stimulus Conditions for Experiment 1

Condition	Classic Switch	Two Lags	No Switch	No Train
Classic switch	×			
Two lags	8, 10, 12, 14	×		
No switch	4, 6, 8, 10	4, 6	×	
No train	n.s.	12, 14	2, 4, 6, 8	×

Note—Numbers in the table specify delays that were significantly different ($p < .05$) between stimulus conditions according to t tests, using the Bonferroni correction for multiple comparisons.

sic switch condition is quite close to that when the train is absent: 38% at 2 msec, rising to 74% at 14 msec.

The critical manipulation in the present study is seen in the two-lags condition. Our hypothesis was that having a second lag during the train on the same side as that at which the lagging sound would be after the switch would eliminate the breakdown in echo suppression usually observed. Lag B's presence during the train would inform the listener that a reflecting surface existed on that side, so that a switch in Lag A's location to the other side would provide no new information about room acoustics and, hence, no drop in echo threshold. Our hypothesis was upheld: Having a second lag dampened the effect of switching lead and lag locations. As compared with the classic switch condition, fewer echoes were heard after the switch when a second lag had been present during the train.

A condition (4) $\times$ delay (7) analysis of variance was performed on these data. The main effects of condition [$F(3,60) = 9.44, p < .005$] and delay [$F(6,120) = 20.90, p < .005$] were highly significant, as was the condition $\times$ delay interaction [$F(18,360) = 4.95, p < .005$]. Follow-up comparisons were made of the main effect of condition in the form of t tests, using the Bonferroni correction for multiple comparisons. The buildup in echo suppression induced by the train was shown by fewer echoes being heard following the no-switch condition, as compared with the no-train condition [$t(20) = -4.87, p < .001$]. The effect of switching lead and lag locations was shown by the increased echoes heard in the classic switch condition, as compared with the no-switch condition [$t(20) = 3.88, p < .006$]. Finally, the room acoustics hypothesis was supported by significantly fewer echoes being heard by the subjects in the two-lags condition than by those in the classic switch condition [$t(20) = 4.37, p < .002$]. It is notable that there was no difference between hearing the test burst after a switch in lead and lag stimuli and hearing the isolated test burst [$t(20) = 0.63, n.s.$]. We interpret this to mean that the switch does not enhance the perceptibility of echoes above and beyond the baseline level of the no-train condition.

The strong main effect of delay is due to the well-known phenomenon that as the time delay between the original sound and the reflected sound is lengthened, more echoes are heard. The condition $\times$ delay inter-

action indicates that stimulus parameters were differentially affected by delay. To follow up this interaction, we performed pairwise comparisons between the conditions at each delay, again using the Bonferroni correction for multiple comparisons. Table 2 shows the comparisons that were significantly different from one another at each delay. First, there was strong evidence for the buildup in echo suppression. When a train preceded the test burst in no-switch, as compared with no train, significantly fewer echoes were reported on delays of 2–8 msec. In addition, the Clifton effect can be seen in the comparison of the no-switch versus the classic switch conditions; more echoes were heard after the switch at delays of 4–10 msec, and this approached significance at the 2-msec delay ($p < .06$). Both of these findings replicate previous work in our laboratory (Clifton & Freyman, 1989; Freyman et al., 1991) and in others (Grantham, 1996; Yost & Guzman, 1996). The critical comparisons for the room acoustics hypothesis are those between the two conditions that had a switch in lead and lag locations for the test burst. These are shown in Table 2 as comparisons between the classic switch condition and the two-lags condition. The hypothesis was partially supported. The subjects heard significantly fewer echoes on the test burst when a second lag was present during the train at delays of 8–14 msec, but not at shorter delays (2–6 msec). Furthermore, it was predicted that the two-lags condition would look much like the no-switch condition, but the two curves cross. These curves differed at 4- and 6-msec delays, but otherwise they were not statistically different. Curiously, the two-

Figure 2. The percentage of total trials on which listeners reported hearing an echo, plotted for each condition as a function of delay between leading and lagging sounds in Experiment 1. Each datapoint is the average of 21 subjects, with error bars for the standard error of the mean.

Table 3
Stimulus Conditions for Experiment 2

Condition	Train	Test
No switch (buildup)	lead 45° left lag 45° right	lead 45° left lag 45° right
Classic switch (one echo)	lead 45° right lag 45° left	lead 45° left lag 45° right
Two lags (different sides)	lead 45° right Lag A 45° left Lag B 55° right	lead 45° left lag 45° right
Two lags (same sides)	lead 45° right Lag A 45° left Lag B 55° left	lead 45° left lag 45° right

lags curve was more or less flat across delays, whereas all the other conditions were affected in the expected manner of more echoes being heard at longer delays. There is no ready explanation for why delay did not affect the two-lags data in the expected manner, but this matter will be taken up again in the General Discussion section.

EXPERIMENT 2

Although support for the room acoustics hypothesis was upheld in Experiment 1, the second lagging sound may have exerted a general effect on the subjects' perception, such that the mere presence of a second lag during the train was responsible for disrupting the effect of switching sides for lead and lag. Our hypothesis says that location is critical, that a lagging sound must be on the side where the lag will be located after the switch. A study by Yost and Guzman (1996) featured two lagging sounds, one left and one center, with the source on the right. They found a strong breakdown in echo suppression when the lead and the lag sides were transposed, with the second lag remaining at center. Their study supports our interpretation of Experiment 1's results that the mere presence of a second lag, independent of its location, is not responsible for disrupting the switch effect.

In an effort to show that the lagging sounds' locations are critical, a second experiment was run in which both lagging sounds were located on the same side during the train. After the switch, Lag A would come from a side at which no echo had been before the switch. We predicted that the second lag would have no effect on performance after the switch. Having two lagging sounds on the same side during the train provides redundant information about a reflecting surface on that side. When the lead and the lag sounds switch sides, the lag's location signals new information about the presence of a reflecting surface, just as in the classic switch condition with only one lag. Echo thresholds should be similar, regardless of whether there was one or two lagging sounds during the train in this case.

Method

Eight normal-hearing adults participated. The stimuli, apparatus, and general procedures were the same as those in Experiment 1. All the subjects received all the conditions. As before, there were four

conditions, and each condition featured the same procedure of a train of 17 noise bursts followed by a test burst. Three conditions were repeated from Experiment 1—namely, the classic switch condition, the no-switch or buildup condition, and the two-lags condition with the lagging sounds on different sides. The fourth condition also had two lagging sounds during the train, but both were on the same side. We label these contrasting conditions two-lags-S and two-lags-D, respectively. (See Table 3 for specification of all loudspeaker locations for Experiment 2 and Figure 1 for a schematic of loudspeaker arrangements in the anechoic chamber.) Each subject was given two blocks of 49 trials (seven delays, randomly mixed, with 7 trials at each delay) for each condition during a session. Three sessions were carried out over 3 days, with order of condition being randomly selected as in Experiment 1. In Experiment 2, each subject experienced 294 trials (49×6) for each condition.

Results

We predicted that the new condition, two-lags-S, would lower echo threshold in a manner similar to that for the classic switch condition. The condition repeated from Experiment 1, the two-lags-D condition, should again disrupt the effect of switching sides. Suppression of the echoes should remain intact, so that subjects perceive fewer echoes in this condition. Data from all four conditions are presented in Figure 3. Again, when only a single lead and lag were present, a large buildup in echo suppression was observed when locations did not change between train and test bursts (no switch), as compared with when locations were switched (classic switch). Of greater interest, when two lagging sounds were present, their location was critical to the switch event. When both lags were on the same side during the train, this simulated a reflecting surface on that side only and should

Figure 3. The percentage of total trials on which listeners reported hearing an echo, plotted for each condition as a function of delay between leading and lagging sounds in Experiment 2. Each datapoint is the average of 8 subjects, with error bars for the standard error of the mean.

have the same effect as a single lag. In keeping with the prediction, data for the classic switch and two-lags-S conditions are virtually identical at all delays. The effect of switching sides was disrupted only when the two lags provided information about reflecting surfaces on both sides (two-lags-D). This curve was lower than those for the classic switch and the two-lags-S conditions. We conclude that the location of each lag provides vital information about reflecting surfaces. When this information suddenly changed, as in the switch condition and the two-lags-S condition, echo threshold was lowered, and more echoes were reported.

A condition (4) $\times$ delay (7) analysis of variance was performed on these data. As in Experiment 1, the main effects of condition [$F(3,21) = 8.22, p < .001$] and delay [$F(6,42) = 4.08, p < .003$] were highly significant. The condition $\times$ delay interaction [$F(18,126) = 4.12, p < .001$] was also significant, reflecting that conditions had their greatest effect at shorter delays (see Figure 3). When longer delays surpassed the subjects' echo threshold, the various conditions had little effect, because the echo was probably heard during both the train and the test bursts. (We did not measure the subjects' perceptions of the echo during the train, but only for the test burst.) A planned follow-up comparison of the two conditions featuring two lagging sounds during the train yielded $t(7) = -3.03, p < .019$, indicating that the lags' locations were critical for listeners' perception after the switch.

The condition $\times$ delay interaction was also followed up as in Experiment 1. Only three comparisons were significant: two-lags-S versus no switch at 8 msec, classic switch versus no switch at 4 and 10 msec. Because of the numerous comparisons made (six between-groups comparisons at each of seven delays), the Bonferroni corrections required a t greater than 3.56, which has a $p < .009$ when uncorrected but misses significance at $p < .055$ when corrected. If comparisons are taken at the uncorrected significance levels, the expected pattern emerges. When both lagging sounds were located on the same side during the train, significantly more echoes were reported at 2, 4, 8, and 10 msec, as compared with when the lagging sounds were on opposite sides. Likewise, the classic switch condition yielded more echoes than did the two-lags-D condition at 2, 4, 6, 8, 10, and 14 msec. As in Experiment 1, the two-lags-D condition was higher than the no-switch condition at 4 and 6 msec, but was not different elsewhere.

The data for individual subjects were examined in order to compute echo threshold, defined as the delay at which an echo was reported on 50% of trials in a condition. Thresholds were interpolated between delays that crossed the 50% boundary. Conservative estimates of echo threshold were made, in that the range of thresholds allowed was bounded by the delays actually presented, although clearly the threshold for some subjects was outside 2–14 msec. Specifically, a threshold of

Figure 4. Data for 4 subjects in Experiment 2 who responded to stimulus conditions as a psychometric function of delay.

Table 4
Echo Thresholds (in Milliseconds) for 4 Subjects
in Experiment 2

Subject	Classic Switch	Two-Lags-S	Two-Lags-D	No Switch
1	2.0	2.0	5.0	10.8
2	7.0	7.5	10.1	8.9
4	4.4	3.3	14.0	12.0
6	3.1	2.9	4.6	7.6
<i>M</i>	4.1	3.9	8.4	9.8
<i>SD</i>	2.2	2.5	4.5	1.9

2 msec was assigned when a subject reported 50% or greater echoes for all delays, and 14 msec was assigned when a subject never reached 50%. Figure 4 displays data for 4 subjects who had an orderly increase in the number of echoes heard as a function of delay. Means and standard deviations of echo threshold are shown in Table 4 for these subjects. The predicted differences among conditions are clear for these subjects, with the classic switch and the two-lags-S conditions virtually identical ($M = 4.1$ and 3.9 msec, respectively) and the no-switch and the two-lags-D conditions closely grouped (9.8 and 8.4 msec, respectively).

On the other hand, 4 of the 8 subjects did not show an orderly psychometric function across delays for *any* condition. Figure 5 displays the data for these subjects, whose responses are generally flat across delays and conditions, although the overall probability of hearing echoes varied greatly across subjects. Subject 5 always

reported echoes above the 50% threshold, and Subject 8 never reported echoes above threshold. We did not screen (except for normal hearing) or exclude any subjects in Experiment 2, nor did we run extensive practice trials to achieve stable performance or individualize the range of delays given. Such procedures are common in psychoacoustic experiments and obviously have merit. Large individual differences have been previously reported in echo threshold and buildup (Clifton et al., 1994; Grantham, 1996; Yang & Grantham, 1997). For example, Grantham screened and excluded 4 out of 29 subjects who could not discriminate the lag's position reliably, even at 90-msec delay. When studying the buildup phenomenon, Freyman et al. (1991) screened 9 subjects to get 7, and Grantham found that 8 out of 25 subjects showed little or no buildup. The lack of screening and sufficient practice trials appears to have diluted the effects of our stimulus manipulations. Differentiation among our stimulus conditions depended on subjects' basic sensitivity to the effects of time delay between lead and lag. Without such sensitivity, it was impossible to demonstrate the influence of stimulus conditions for those subjects.

GENERAL DISCUSSION

In two experiments, we showed that the fusion aspect of the precedence effect can be modulated by temporal and spatial variations of sound preceding the test event.

Figure 5. Data for 4 subjects in Experiment 2 who were insensitive to delay in any stimulus condition.

As in a previous study (Freyman et al., 1991), we found that the amount of buildup in echo suppression produced by the train is dependent on the delay between lead and lag sounds. When stimuli remained in the same positions for train and test bursts, the lagging sound was heard less often at shorter delays (2–10 msec), whereas at longer delays performance approached that of a control condition having a single stimulus pair with no preceding train. Psychometric functions of delay plotted against reports of the echo in both Experiments 1 and 2 confirmed the reliability of the effect of time delay.

In terms of spatial effects, the first experiment found that repositioning the lead and the lag sounds by switching sides and the introduction of a second lag sound before the switch affected performance. The former manipulation was a replication of the Clifton effect, whereas the latter was an attempt to understand the mechanisms responsible for it. When the preceding train featured two lagging sounds positioned on opposite sides, the effect of switching lead and lag sounds was significantly decreased, as compared with a train with only one lag. We interpreted this finding in terms of the room acoustics hypothesis—namely, that the Clifton effect is due to an unexpected lagging sound from a location where none had been before. Thus, stimulus events that produce a sudden lowering of echo threshold simulate the appearance of a new reflecting surface in the room. The second experiment provided evidence that the location of the second lagging sound was critical. When both lag sounds were on the same side, rather than on opposite sides, they provided redundant information about a reflecting surface on that side. In this case, switching the lead and the lag led to more echoes being reported, similar to the case of one lag during the train. Yost and Guzman (1996) found that a second lag sound placed in the center position that remained on during both train and test clicks had no effect, which provides additional support to our claim that redundant second echoes do not disturb the Clifton effect.

In both experiments, there were two conditions in which the lagging sound was already present on the right during the train and at the test burst: the no-switch condition in both experiments, and the two-lags condition in Experiment 1 and the two-lags-D condition in Experiment 2. We had predicted that performance would be similar in all of these conditions. The data for the conditions with two lagging sounds, however, lie somewhere in between those for the no-switch and those for the classic switch conditions (see Figures 2 and 3). Although conceived as conditions in which there was no large change in room acoustics, the conditions with two lags actually had two changes between train and test that should be noted. Lag B at 55° on the right during the train was omitted during the test burst; Lag A (whose delay was half that of Lag B during the train) was introduced at 45° right. In designing these stimulus conditions, we wanted to keep the test burst exactly the same for all conditions. The classic switch has the lead and the

lag switching locations, so this put Lag A at 45° right, in the lead's previous position. Listeners may have been sensitive to the 10° change in the lagging sound's position, to its shortened delay, or to both changes. This could account for why the conditions with two lags are in between the no-switch and the classic switch conditions. The former had no change in room acoustics between train and test, whereas the latter had the most dramatic change. The changes in conditions with two lags were more subtle than the classic switch, but the data suggest that they were noticed by some listeners.

If the two experiments reported here were the only evidence supporting the room acoustics hypothesis, this would be slim documentation. Some of the strongest support for the hypothesis comes from a series of studies by Blauert and Col (1989, 1992). Earlier, we described their study in which the switching of lead and lag sides was performed multiple times. If the switch was performed regularly, so that subjects could anticipate it, they eventually stopped experiencing the breakdown of the precedence effect. Modulation of the switch effect is but one of several phenomena predicted by the room acoustics hypothesis. Previous work has tested other predictions, such as that a sudden movement in depth of the reflecting surface or a change in the absorptive qualities of the surface would lower echo threshold. Clifton et al. (1994) provided evidence that either shortening or lengthening the delay between the leading and the lagging sounds lowers echo threshold. That manipulation simulated a sudden movement of the reflecting surface either toward or away from the listener. In a subsequent study, we showed that simulating changes in the absorptive qualities of the reflecting surface also lowers echo threshold (McCall, Freyman, & Clifton, 1998). When a low-pass filtered lag during the train was changed to a high-pass filtered lag at test burst (or vice versa), subjects' perception of the echo was enhanced. Blauert and Col (1992) found that when lagging sounds were omitted during a train, simulating the sudden removal of a reflection, this produced a disruption of echo suppression. This result is similar to those in an experiment reported in Freyman et al. (1991), which featured a train with no lag followed by the introduction of a new lagging sound. When a single click was presented throughout a train, followed by a test pair that had the same lead click now followed by a lag click (simulating the sudden appearance of a reflecting surface), subjects heard both the lead and the lag clicks. Thus, either the precipitous removal or the new appearance of a reflecting surface banishes echo suppression.

Control experiments have shown that variations in the lagging sound that do not simulate a change in room acoustics have no effect on echo threshold. For example, when both lead and lag sounds changed in frequency or intensity from train to test, discrimination of the echo did not change (Clifton et al., 1994). These changes signify that the original sound's frequency or intensity varied, with accompanying changes in the reflected sound, and

were not expected to produce a drop in echo threshold. Likewise, when both lead and lag positions were moved laterally but remained on the same side, echo threshold was not affected (Yost & Guzman, 1996). When the lag remains on the same side, a lateral shift does not simulate the appearance of a new reflection. All of this work attests to the mutability of the echo threshold and to listeners' sensitivity to information carried in reflections specific to room acoustics.

As with many biological processes, the more we study the precedence effect, the more complex it turns out to be. Beginning with the seminal article by Wallach, Newman, and Rosenzweig (1949), this half-century of research has revealed unsuspected facets of the phenomenon (for reviews, see Blauert, 1997; Litovsky, Colburn, Yost, & Guzman, 1999; Zurek, 1987). Growing evidence suggests a significant role for cognitive processes in the precedence effect. Comprehensive reviews of this literature may be found in Clifton and Freyman (1997) and in Blauert's *Spatial Hearing*, in a section called "The Precedence Effect: A Case for Cognition" (1997, pp. 409–424). The basic idea is that listeners' expectations about ongoing sound affect their perception of echoes. The room acoustics hypothesis refines and limits this idea to specific predictions. In this, we are following Benade's (1976) suggestion that reflections serve the purpose of informing the listener about the space in which a sound is made: "Our auditory apparatus is able very quickly to 'learn' the scattering behavior of nearby objects . . . and can separate the characteristic nature of those changes from the identifying features of the original sound" (p. 209). The study of the perceptual ability to use room acoustic information is just beginning, but experiments such as those reported here indicate an exquisite sensitivity to the information contained in reflected sound. The buildup and breakdown phenomena are dramatic examples of how this information gets used. The mechanisms responsible for these effects are not well understood, but cognition and attention are implicated. Cuing mechanisms are well established in visual perception (e.g., Kahneman & Treisman, 1984; Posner & Peterson, 1990) but have been less studied in the auditory system. It is our hope that research on the cognitive aspects of auditory perception will contribute further understanding of both cognition and hearing.

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