Localization of sound in rooms, III: Onset and duration effects

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The steady-state sound field of a sine tone does not provide useful localization information in a room. Nevertheless, listeners can localize a sine tone in a room if it has an onset transient which allows the precedence effect to operate. In the present study, we made a quantitative assessment of onsets and the precedence effect by systematically varying onset duration from 0 s (impulsive), where the precedence effect is maximal, to 5 s, where there is no precedence effect at all. We also assessed listeners' sensitivity to the steady-state sound field under impulsive conditions by varying the total duration of tone pulses. Our experiments were conducted in a room with a single acoustical reflection having various directions and delays, and in an anechoic room. The results for tones of various frequencies (500 and 2000 Hz) and sound-pressure levels (65 and 40 dBA) indicate the following: (1) Localization in rooms is facilitated by onsets even if the onsets are as long as 100 ms. (2) The facilitation depends upon the peak intensity of the tone, as well as the onset duration, suggesting that onset *rate* is critical for the precedence effect; our results are most consistent with rate expressed as an increase in sound pressure per unit time. (3) The facilitation also depends upon the reflection delay time for a room; gradual onsets take on much more importance for the precedence effect in rooms with long delays. (4) As onsets begin to lose their effectiveness listeners become increasingly "misdirected" by invalid cues in the steady-state sound field. The pattern of misdirection suggests a perceptual averaging of cues over an interval more than an order of magnitude longer than previous estimates of the summation window for the precedence effect. (5) The pattern of misdirection varies with the frequency of a tone, due to frequency-dependent interference effects in a room, but it is independent of signal level. (6) Localization of an impulsive sine tone in rooms is very insensitive to the pulse duration; this suggests that binaural inhibition models of the precedence effect must be supplemented by an evaluative component that we term the "plausibility hypothesis."

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INTRODUCTION

This is a report on our third experimental investigation of auditory localization in rooms. The first investigation (Hartmann, 1983, referenced below as paper I) was conducted in a concert hall with variable acoustics, and used reverberation times ranging from 1 to 5 s. The second investigation (Rakerd and Hartmann, 1985, referenced as paper II) was conducted in a room with a single reflecting surface. For both of these environments we observed a significant difference in the localizability of the two classes of sounds illustrated in Fig. 1(a). In the first class were brief tone pulses with abrupt onsets and offsets. Typically we used 50-ms, 500-Hz tone pulses. In the second class were sustained tones (i.e., tones without offsets) having slow onsets (about 7 s) and thus no transient character. We observed that the impulsive tones were localized quite accurately in rooms, while the slow-onset tones were localized poorly, often so poorly as to reach the upper limit of our ability to measure the localization error. These observations confirmed the critical importance of transients for localization in rooms. Transients trigger the precedence effect (Wallach *et al.*, 1949; Haas, 1951; Gardner, 1968) which defeats much of the interference of room reflections.

In the present investigation, we focused our attention particularly upon the onset transient and asked a number of questions about its contribution to localization in rooms. Among them were the following: How does localization ac-

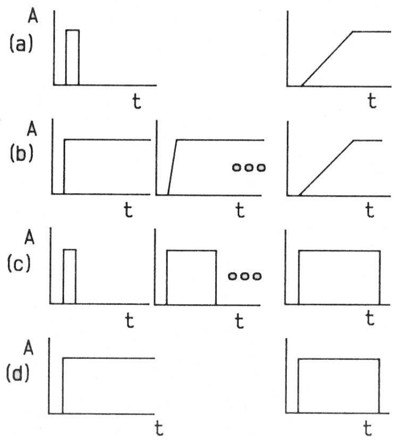

FIG. 1. (a) Amplitude envelopes of stimuli compared in papers I and II. (b)–(d) Amplitude envelopes of stimuli compared in the present work (see text).

curacy change as the onset of a tone is made more gradual, i.e., as the duration of the onset is increased? Does localization accuracy depend upon onset duration *per se* or upon the onset rate? Do onset effects vary with changes in the direction of room reflections and/or the delay of those reflections? Do onset effects vary with the frequency of a tone? How do these effects compare with the consequences of onsets for the lateralization of tones and noise as reported in the literature on headphone experiments? To address these questions we asked subjects to make azimuthal localization judgments for sustained tones differing only in their onset durations, as illustrated in Fig. 1(b). We used onset durations ranging from 0 to 5000 ms.

The present study also included several experiments assessing the influence of tone duration and offset on localization in rooms. Tone duration effects were tested by experiments using short and long duration amplitude envelopes, as shown in Fig. 1(c). The perceptual contribution of an abrupt offset was studied by comparing data for corresponding conditions in the onset-duration and tone-duration experiments, as illustrated in Fig. 1(d).

I. GENERAL METHODS

The following methods were common to all of our experiments.

A. Subjects

The subjects were three men and one woman ranging in age from 21 to 33. All of the subjects had normal hearing according to self report. Two of the subjects (B and J) were experienced participants in psychophysical studies of hearing; subject B was one of the authors and had previous experience in localization experiments.

B. Sound sources

Stimuli were presented from 12 midrange drivers with integral rear baffles (Pioneer SS908), selected from a lot of 24 for best-matched frequency response. Each driver was mounted on a (5.5 in. × 11 in. × 0.75 in.) board with a 0.75-in. hole drilled in front of the center of the cone to allow sound to pass. These sources were arranged in a horizontal arc and numbered 1 through 12, from left to right. Subjects were seated in a chair which faced the center of this arc at a distance of 10 ft from all of the sources. With this arrangement there were 3° of angular separation between neighboring sources; 0.36° of this was taken up by source aperture. Chair height was adjusted such that all subjects' ears were 46 in. above the wire-grid floor of the chamber. The source apertures were 44 in. above the grid.

C. Testing procedure

The subjects were tested individually. Each went through a different order of testing in the various experiments and experimental conditions. For each condition of each experiment a subject completed 1 run of 100 trials, 10 presentations from each of the 8 centermost speakers in the source array and 5 from each of the 4 outermost speakers. The order of these presentations was randomized with the constraint that no source was presented more than twice in succession.

A subject was given the forced-choice task of reporting the horizontal location of the sound heard on each trial. The numbers attached to the sources (1–12) corresponded to 12 possible response alternatives. Other numbers, less than one and growing progressively more negative, were placed along the walls of the chamber to mark locations to the left of the source array. Locations to the right of the array were marked with numbers increasingly greater than 12. Last, subjects were given a diagram showing the possible responses for 360° of arc. Responses were reported via an intercom; no feedback was given as to response accuracy.

This testing procedure is a modified version of the source identification method employed in papers I and II. A comparison between this modified source identification method and the original method is given in the Appendix.

D. Rooms

The experiments were conducted in rooms having only one acoustically reflective surface. The details of this experimental arrangement were given in paper II. Briefly, it consists of an 11 ft × 15 ft × 8 ft anechoic chamber (IAC 107840) bordered on one side with a 4 ft × 8 ft panel. The panel has an acoustical reflection coefficient estimated to be 1.0 at frequencies of interest. Across experiments the position of the panel is varied to create different rooms. In this study we created the following rooms:

1. Wall, brief delays

The reflective panel was parallel to and 3 ft to the left of a line between the listener and the center of the source array, producing a room with wall reflections of brief delay (the WBD room). In paper II this room configuration was called "L." With this arrangement, the average reflection delay time for the 12 sources was 1.5 ms. The specific delay for each source and the corresponding reflection angle are reported in Table I, which also shows delay times and reflection angles for the other room configurations.

TABLE I. Delay of reflections and (angle of reflections), both relative to the direct sound. The delay times are in milliseconds; the angles (in parentheses) are in degrees.

Source	Wall brief delay	Ceiling brief delay	Wall long delay
1	0.1 (2)	1.5 (31)	7.0 (41)
2	0.4 (7)	1.5 (31)	7.5 (44)
3	0.6 (12)	1.5 (31)	7.9 (48)
4	0.9 (18)	1.5 (31)	8.3 (52)
5	1.1 (23)	1.5 (31)	8.8 (56)
6	1.4 (28)	1.5 (31)	9.2 (59)
7	1.6 (33)	1.5 (31)	9.6 (63)
8	1.8 (39)	1.5 (31)	10.0 (67)
9	2.1 (44)	1.5 (31)	10.4 (70)
10	2.3 (49)	1.5 (31)	10.7 (74)
11	2.5 (54)	1.5 (31)	11.1 (77)
12	2.7 (59)	1.5 (31)	11.5 (82)

2. Ceiling, brief delays

In this room the reflective panel was 3 ft above the source array (34 in. above the subjects' ears), creating ceiling reflections of brief delay (CBD). At that distance the reflection delay time was 1.5 ms for all sources, a value equal to the mean WBD delay. A very similar room arrangement in paper II was called "C."

3. Wall, long delays

We created a room with wall reflections coming from the subjects' left at delays much longer than those previously tested (WLD). The delays ranged from 7.0 to 11.5 ms across the sources and averaged 9.3 ms (Table I). To produce these long delays the source array was placed as far to the right as possible in the anechoic room, and the reflective panel as far to the left as possible. The panel was 9 ft to the left of the line from the listener to the center of the source array.

4. Empty room

For comparison, experiments were conducted in the anechoic room without reflecting surfaces, called the "empty" room. Similar experiments were done in paper II with the source identification method. They were done here with the modified method and a larger set of stimulus envelopes.

E. Data analysis

The analysis included four statistics:

1. Mean location judgments: R(k)

We computed the *mean location response* to each loudspeaker source. For a particular source, k, this is symbolized as $R(k)$. If a subject makes M responses r to source k, then

$$R(k)=\frac{1}{M}\sum_{i=1}^{M} r_i. \qquad (1)$$

Values of $R(k)$ are on a scale defined by the source numbers, and they will be reported for all 12 sources.

2. Overall error: ⟨D⟩

Statistic D is the *overall* error of localization in degrees. It is the rms average of the discrepancy between the azimuth of a source and the azimuth of a subject's responses to that source. For source k:

$$D^2(k)=A^2\frac{1}{M}\sum_{i=1}^{M}(r_i-k)^2, \qquad (2)$$

where A is the angular separation of sources in degrees.

3. Variable error

Variable error, symbolized as s, is the standard deviation of a subject's responses. It is computed with reference to the mean response for source k, i.e.,

$$s^2(k)=A^2\frac{1}{M}\sum_{i=1}^{M}[r_i-R(k)]^2. \qquad (3)$$

4. Constant error

Constant error C is the average deviation of the set of responses from the corresponding source, *independent of the "direction" of the deviation*. For source k:

$$C^2(k)=A^2\left(\frac{1}{M}\sum_{i=1}^{M}(r_i-k)\right)^2. \qquad (4)$$

Quantity $C^2(k)$ is the square of the statistic $E(k)$, introduced in paper I. $E(k)$ may be positive or negative according to a listener's bias, and when it is averaged over sources k, cancellations of positive and negative biases can occur. Statistic C is never negative so that such cancellations do not occur. It is a measure of systematic error, no matter what its sign.

With the above definitions, the square of the overall error for a source is equal to the sum of the squares of the constant and variable errors, i.e.,

$$D^2(k)=C^2(k)+s^2(k). \qquad (5)$$

5. Averaging

To calculate the rms statistics reported here, the squared quantities $D^2(k)$, $C^2(k)$, and $s^2(k)$ were averaged over subjects or sources or both, and then the square root of the result was taken. Averaging over subjects is indicated in the text by angular brackets around the corresponding statistic, e.g., $\langle D\rangle$. Averaging over sources is indicated by a bar over the corresponding statistic, e.g., $\overline{D}$. In all cases the averages over sources were computed over the eight centermost sources only (3–10) so as to avoid end effects (see the Appendix). All averages preserve the Pythagorean relation that the square of the overall error is equal to the sum of the squares of the constant error and the variable error.

II. THE ONSET DURATION

In papers I and II the stimulus signals either had instantaneous onsets or else slow onsets with a rise time of 7 s. In the present series of experiments we varied the onset duration and observed the effects upon localization accuracy. The purpose of this series was to gain quantitative information on the operation of the precedence effect in rooms. There were six different experiments. Across experiments 1–3 stimulus signals were held constant and the direction and delay of room reflections were varied. Across experiments 1, 4, and 5, room reflections were held constant and the frequency and intensity of the stimulus were allowed to vary. Experiment 6 was carried out in the empty anechoic room.

A. Experiment 1: The standard

In experiment 1 we studied the effects of changing onset duration using a stimulus (500-Hz sine) and a room geometry (the WBD room) familiar from our previous work. The conditions of experiment 1 became the *standard* from which experiments 2–5 systematically departed.

1. Method

Stimuli for experiment 1 were 500-Hz sine tones turned on at positive-going zero crossings and left on until subjects made a localization response. The onset envelope was a linear ramp with durations of 0, 5, 10, 50, 100, 500, 1000, and 5000 ms. The steady-state level was 65 dBA, as measured at the subjects' position under anechoic conditions.

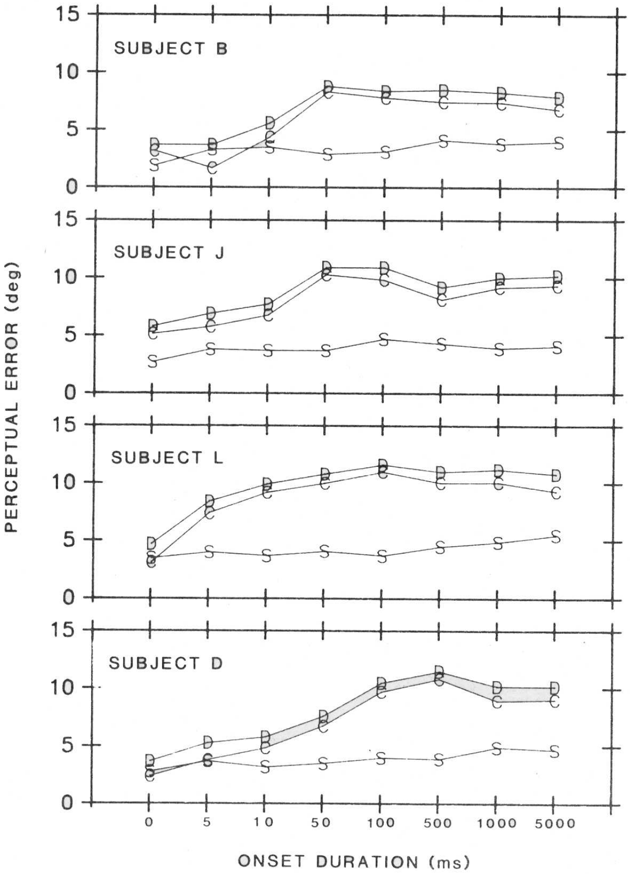

FIG. 2. Overall $\overline{D}$, constant $\overline{C}$, and variable $\overline{s}$ errors of localization in a room with left wall reflections of brief delay, as functions of the onset duration of a sustained tone. Each panel represents the performance of a different subject. The constant error is a meaure of the component of overall error due to bias. The variable error is a measure of the component due to variability in responses.

2. Results and discussion

a. Individual results for $\overline{D}$, $\overline{C}$, *and* $\overline{s}$. Figure 2 gives the overall $\overline{D}$, constant $\overline{C}$, and variable $\overline{s}$ error for each subject as a function of onset duration. The results for subjects B and J (top two panels) are very much alike. For both, overall and constant errors increase steadily with onset duration up to a plateau which is reached at 50 ms, while variable error remains relatively constant throughout. The data for subject L (third panel) and subject D (bottom panel) are similar to the data for B and J except that the plateau in overall and constant error is reached at 100 ms for D, and the negative curvature for L makes it less easy to identify a plateau.

One conclusion that can be drawn from these results is that a 7-s onset duration, used in papers I and II to eliminate the effect of onset cues, exceeds the onset duration actually necessary to eliminate those cues by more than an order of magnitude. However, the onset durations of 7 and 25 ms used, respectively, by Yost (1977) and McFadden and Pasanen (1976) to try to avoid onset cues in lateralization experiments may well be too brief.

For all listeners the variable error s is almost independent of the onset duration. That means that the increase in overall error with increasing onset duration occurs because listeners are increasingly misled by localization cues in the steady-state sound field, and not because their judgments are increasingly erratic. This observation is the first aspect of a pattern which we shall call "misdirection."

b. Variability in $R(k)$. The function $R(k)$ shows the mean response given by a subject to a source k. Its average $\langle R(k)\rangle$ for three subjects (B, J, and L) is shown in the leftmost panel of Fig. 3. The function for the fourth subject was very similar. The different functions within the panel represent different stimulus onset durations, with larger durations represented by plotting symbols with larger numbers. (The

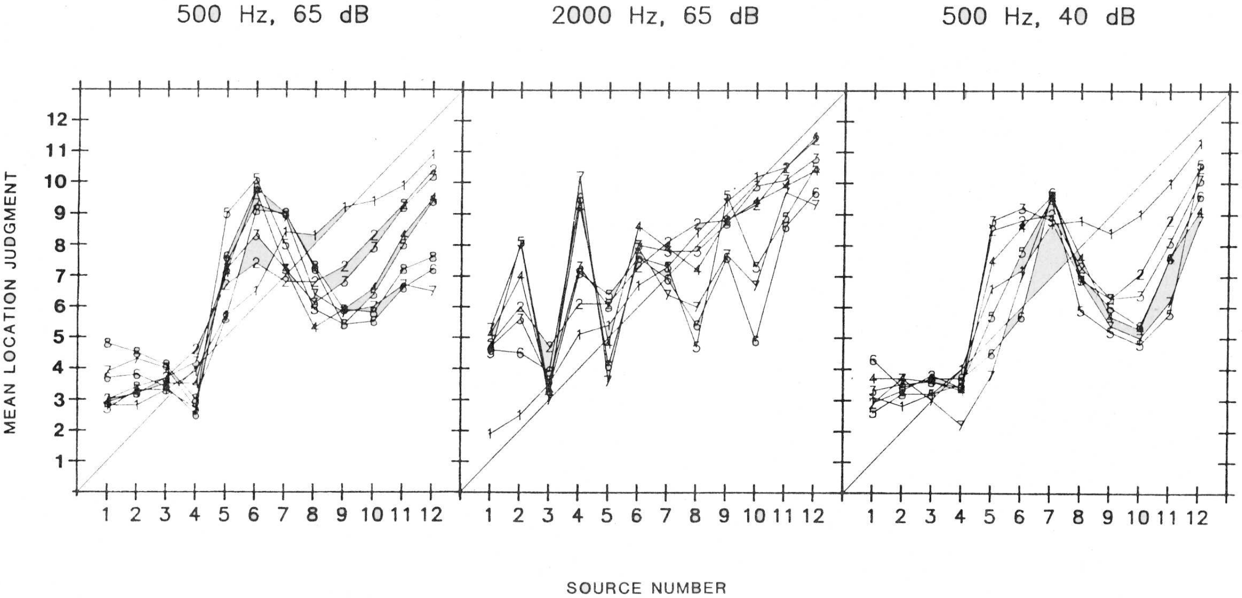

FIG. 3. Average modified-source-identification-method reponse to each of 12 sources in a room with left wall reflections of brief delay. Each panel represents a different combination of stimulus frequency and intensity. Each function within a panel represents a different stimulus onset time: *1* = 0 ms, *2* = 5 ms, *3* = 10 ms, *4* = 50 ms, *5* = 100 ms, *6* = 500 ms, *7* = 1000 ms, *8* = 5000 ms.

other two panels in Fig. 3 show data from experiments 4 and 5, presented below.)

For onset durations of 50 ms or greater (plotting symbols 4–8) the deviations in $\langle R(k) \rangle$ from k itself [statistic $\langle E(k) \rangle$] are often large. There are 31 instances in the figure where the difference exceeds one speaker spacing. Of these, the difference exceeds the *standard deviation* in $R(k)$, computer across subjects, in 27 instances. That standard deviation, averaged over k, was 1.0 (i.e., one interspeaker separation of 3°) for instantaneous onsets and it increased to 1.7 for the longest onset duration. These variability statistics show that different listeners are misled in similar ways by the localization cues in a steady-state sound field. This is a second aspect of misdirection.

The plot of $\langle R(k) \rangle$ in Fig. 3 shows that for instantaneous onsets the responses are close to the 45° line, where response number $\langle R(k) \rangle$ equals source number k. For long onset durations (100 ms and longer) the responses deviate considerably from k, because of the inappropriate cues in the steady-state sound field (paper II). For onsets of intermediate duration (5, 10, and 50 ms) the $\langle R(k) \rangle$ plots tend to lie between the plots for instantaneous and long onsets.[1] There are two ways in which this might occur. One possibility is that the responses are divided into two groups, one group close to the 45° line and the other group far removed. That would put the mean at intermediate values, as observed in Fig. 3. An examination of the confusion matrices, however, shows that this is not what happens. Instead, the confusion matrices show that, for onset durations of 5–500 ms, listeners rather consistently perceive the source to be at an azimuth which is between the perceived azimuths for instantaneous onsets and the longest onset durations. This is evidenced, for example, in the modal responses to the sources, which systematically move from the brief duration values to the long duration values as the duration of the onset increases. Therefore, the fact that $\langle R(k) \rangle$ for intermediate durations lies between the plots of $\langle R(k) \rangle$ for brief and long durations does not indicate the results of experimental data averaging. Rather, it indicates *perceptual averaging*, which is a third aspect of misdirection. By perceptual averaging we mean that the auditory system somehow averages physical localization cues over a span of time.

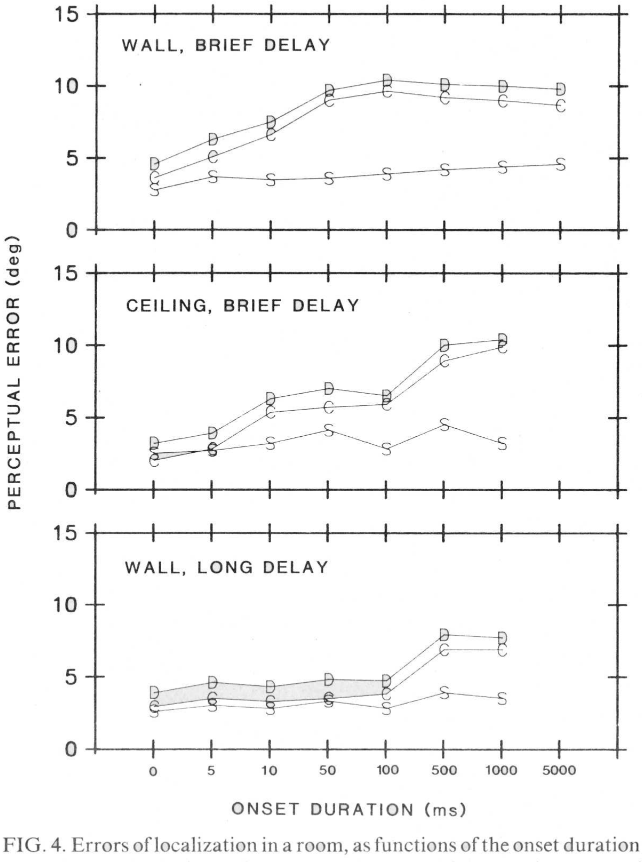

FIG. 4. Errors of localization in a room, as functions of the onset duration of a sustained tone. Each panel represents average performance in a room with a particular direction and delay of acoustical reflection as indicated.

Our informal observations are that perceptual averaging is unconscious, and that it results in the perception of a source stably situated at some point in a room. It is extremely rare for the image of a source to move, even for tones that are several seconds long. The $R(k)$ data cited above indicate that perceptual averaging takes place over an interval of tens or hundreds of milliseconds, the time scale over which the modal response moves in our data. Such an averaging time is far longer than previous estimates of the summation window for the precedence effect, which are of the order of a millisecond (Blauert, 1971, 1983; Zurek, 1980). Those estimates were based upon experiments using clicks and noises as stimuli; our experiments used sine tones.

c. Average results for the standard experiment. The top panel of Fig. 4 gives overall, constant, and variable errors averaged over the four subjects (i.e., $\langle \overline{D} \rangle$, $\langle \overline{C} \rangle$, $\langle \overline{s} \rangle$). These data afford our best estimate of the contribution of onsets in the WBD environment. They indicate that with a lateral reflection of brief delay, onset duration must be 100 ms or less in order for the onset to have any effect on azimuthal localization. The effect of the onset for short onset durations is to enhance the accuracy of localization by reducing constant error. Its effectiveness decreases monotonically with increasing onset duration within the regime of these short durations.

There is an interesting parallel to these findings in the literature on lateralization. Kunov and Abel (1981) and Abel and Kunov (1983) performed a rivalry experiment in which the interaural onset time difference caused a tone to be lateralized to one side of the head, whereas the interaural phase difference in the steady-state portion of the signal (200 ms) caused the tone to be lateralized to the other side. They found that increasing the onset duration of the tone from 5–200 ms resulted in a progressively diminishing, but still positive, contribution of the onset cue to lateralization. Their limit of 200 ms can be compared with our limit of 100 ms.

That onsets affect the lateralization of signals with long duration (*circa* 200 ms) conflicts with the conclusions of investigations which have used noise bands as stimuli (e.g., Tobias and Schubert, 1959; Perrott and Baars, 1974). There, the onsets (and offsets) negligibly affected the lateralization of noise bursts when those bursts had full-on times of 200 ms or more. It seems clear that the difference between the results of these lateralization studies is due to the difference between a tone and a noise band. Paper I suggested that this results from the fact that noise is, in effect, a series of small impulses, i.e., a series of transients that continuously invoke *binaural inhibition* (Zurek, 1980; Blauert, 1983) as an aid to localization. The impact of a transient onset cue to lateralization may be greatly diminished if the fine structure of the signal is itself transient. By contrast, a steady tone has no ongoing impulsive nature and the onset cue assumes much greater importance.

B. Experiment 2: A different direction of reflection

Experiment 2 differed from the standard experiment in that the acoustical reflection came from above; here, we used a vertical reflection from the ceiling. Reflection delay time was again brief, 1.5 ms, a value equal to the mean reflection delay time in the WBD room.

1. Method

The reflective panel was suspended above the sources to produce the CBD room configuration. The stimuli were the same as in the standard experiment except that the 5000-ms onset condition was omitted. Subjects and procedure were also the same as for the standard experiment except that subject L was not tested at the 100-ms onset duration.

2. Results and discussion

The error data for the CBD room are shown in the middle panel of Fig. 4. For the longest onset durations the error $\langle \overline{D} \rangle$ is comparable to that for the wall in experiment 1. For shorter durations the error is usually less than in experiment 1, in agreement with the observation made in papers I and II that vertical reflections are usually less disruptive of azimuthal localization than are lateral reflections when localization is aided by the precedence effect. There is a plateau in $\langle \overline{D} \rangle$ and $\langle \overline{C} \rangle$ between 10 and 100 ms. This occurs mainly because of unexpectedly small errors for all three subjects at the 100-ms onset duration. Possibly this represents a learning effect, because the runs at 100 ms were done somewhat later than most of the other runs with the ceiling. Possibly the plateau represents a real effect which we do not understand. The error data from listener L, not tested at 100 ms, are actually rather flat from 10 to 500 ms. The $\langle R(k) \rangle$ curves for onset durations of 50 to 100 ms are also almost identical. Otherwise, the results with the ceiling reflection resemble those with the wall reflection. In particular, the variation in overall error is almost entirely attributable to variation in the constant error, i.e., to misdirection. Also, the extent of misdirection increases monotonically with onset duration over a considerable interval. An analysis of subjects' modal responses again indicated that this increase was the result of perceptual averaging.

C. Experiment 3: Long delays

This experiment was a complement to experiment 2. There the reflection delay time was similar to the standard but the reflection direction was different. Here, the reflection direction was the same as the standard but the reflection delay was greatly increased. The mean delay time was 9.3 ms in this experiment, a sixfold increase over the mean delay in the standard experiment.

1. Method

The source array and reflective panel were arranged in the WLD room configuration. All other aspects of the method were identical to experiment 2.

2. Results and discussion

Increasing the delay time of the acoustical reflection resulted in a large change in the effect of the onset of the tone, as can be seen by comparing the upper and lower panels of Fig. 4. For onset durations from 0 to 100 ms the localization errors are constant and small in this experiment. They are all essentially equal to the error for the wall in experiment 1 for *instantaneous* onsets. As the onset duration increases to 500 ms, there is a steep rise in localization error. As was the case with brief delays, the variation in overall error is attributable to misdirection.

It should be noted that in the WLD room reflections were not only delayed relative to the standard, but were also reduced in amplitude, on the average by a factor of three. Therefore, the reflections caused a smaller change in the sound field relative to a free-field condition. We estimate that the change in ongoing interaural intensity differences (IID), measured in dB, was a factor of two less than for the standard and that the change in ongoing interaural time differences (ITD) was also a factor of two less. Therefore, it is not surprising that at the longest onset durations, where only ongoing cues are available, the overall error in this experiment ($\langle \overline{D} \rangle = 7.7°$) was several degrees smaller than in the standard ($\langle \overline{D} \rangle = 10.0°$). The plot of $\langle R(k) \rangle$, not shown here, reveals that the most dramatic difference between experiments 1 and 3 for long onset durations was that sources 10, 11, and 12, the furthest from the wall, were accurately localized in experiment 3, but not in experiment 1.

What is most interesting about experiment 3 is that localization errors did not increase as the onset duration increased from 0 to 100 ms. Because the errors did finally show a large increase when the onset duration became as long as 500 ms, we know that the reduction in reflection amplitude could not be solely responsible for the constancy and smallness of the errors below 500 ms. It is not clear how one should interpret this experimental result. The most obvious benefit of a long reflection delay is an increased amount of time to gather information about the onset of a direct sound in the absence of any interference. On the average a listener had an additional 7.8 ms in this experiment compared to the standard experiment. It is possible that the additional time allowed the slower onsets to engage the precedence effect fully, whereas at brief delays they were only partially effective. However, this explanation, like our earlier account of the perceptual averaging of cues, would require that the summation time for the precedence effect be substantially longer than previous estimates.

An alternative explanation is that the increased reflection delays of this experiment allowed listeners to use ongoing cues. In the absence of any interference, ITD and IID give reliable information about the location of a direct sound. One could imagine that with 9.3 ms to attend to the direct sound, in the absence of any reflection, listeners learned something from IID and ITD, though, of course, the

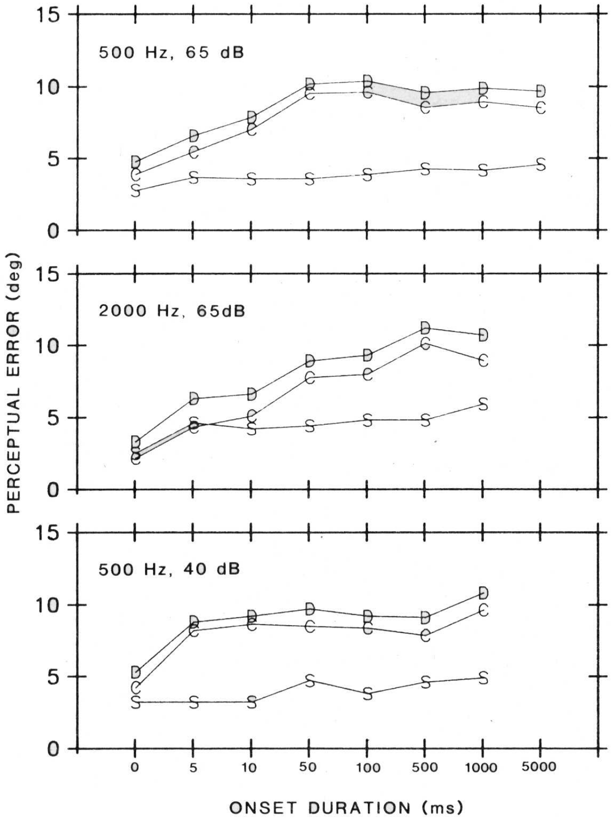

FIG. 5. Errors of localization in a room with a left wall reflection of brief delay, as functions of the onset duration of a sustained tone. Each panel represents average performance for a particular combination of tone frequency and intensity as indicated.

signals were still rising during this time. Whatever the cause, it is clear that an increase in reflection delay time greatly facilitates localization in rooms.

D. Experiment 4: High frequency

At the relatively low frequency of the standard experiment, ongoing ITD cues provide usable localization information but at higher frequencies, greater than 1500 Hz, ongoing ITDs become ineffective (Stevens and Newman, 1936; Sandel *et al.*, 1955; Mills, 1958). The purpose of experiment 4 was to determine how signal onset duration would affect localization in rooms in this high-frequency region.

1. Method

The room was arranged in the WBD configuration as in the standard experiment. The frequency of the stimulus tones was increased to 2000 Hz and intensity was again 65 dBA. The three subjects (B, J, L) participated in this experiment, except for the 100-ms condition from which subject L was absent. All other aspects of the method were as in the standard experiment.

2. Results and discussion

a. $\overline{D}$, $\overline{C}$, *and* $\overline{s}$. The error data are presented in the middle panel of Fig. 5, which gives the averaged performance of the three subjects for 2000 Hz. These data may be compared to the averaged performance of the same three subjects at 500 Hz, shown in the upper panel. The comparison shows some differences; however, variation among individual listeners in the 2000-Hz experiment was large enough that we cannot say that the errors for 2000 Hz are actually any different than at 500 Hz.

b. $R(k)$. The left and center panels of Fig. 3 display subjects' mean location judgments for 500 Hz (experiment 1) and 2000 Hz (experiment 4), respectively. The $\langle R(k) \rangle$ curves for slow onsets are much more ragged at 2000 Hz than at 500 Hz. This is an expected result because localization cues become more sensitive to changes in geometry for smaller wavelengths. Surprisingly, however, the variability in $R(k)$ was not larger at 2000 Hz than at 500 Hz; the standard deviation across listeners was about 1.5 speaker separations for both frequencies.

The rapid variation in the $\langle R(k) \rangle$ functions casts some doubt on the validity of our procedure for 2000-Hz tones. It is evident that, in order for the source identification method to provide reasonable error data, the array of sources must be a fine array. In a fine array the structure in $R(k)$ is a slowly varying function of the source number k. For the case of 500-Hz tones this requirement appears to be met. For 2000-Hz tones the array is, at best, marginally fine. To see the effect of an array which is too coarse, one only has to imagine what would have happened if we had done the 2000-Hz experiment using only odd numbered sources. In that case the error data for long onset durations would have been much smaller than for 500 Hz. Alternatively, if we had done the 2000-Hz experiment using only even numbered sources the error data would have been much larger than for 500 Hz. With the array actually used, the structure in $R(k)$ seems to vary as fast as k itself, about four times faster than for 500 Hz, as would be expected. Therefore, the array was perhaps just fine enough to capture the structure in $R(k)$ at 2000 Hz and the error data may be valid.

One thing these data do show unequivocally is that listeners can localize 2000-Hz tones very successfully when those tones have brief onsets. The $R(k)$ functions for 0- and 5-ms onset durations lie very near to the 45° line of the figure, indicating that the true and perceived locations of sources were in close agreement. It is natural to wonder how this high accuracy was achieved given the insensitivity to ITD at high frequency. There are a number of lateralization studies which show that interaural time differences can be useful cues at high frequency if the signal fluctuates (Henning, 1974, amplitude modulation; McFadden and Pasanen, 1976, noise and two-tone complexes; Hafter and Dye, 1983, Gaussian pulse trains). One might imagine, therefore, that ITDs in the onset of a 2000-Hz tone would provide a localization cue. However, in the lateralization experiment most similar to our localization experiment (Abel and Kunov, 1983), it was found that lateralization at 2000 Hz was unaffected by changes in onset phase angle difference ranging from 90° to 225°. This corresponded to a change in ITD of 187 μs. Interaural time differences in the direct sound in our experiment were never more than 150 μs, suggesting that ITD cues could not be used.

Yost *et al.* (1971) showed that lateralization of a single transient by ITD cues requires low-frequency energy. A high-frequency pulse with only interaural time differences could be lateralized only if the onset was abrupt enough to cause appreciable spectral splatter to low frequencies. If our listeners were using ITD cues to localize the 2000-Hz tones, then the errors should have increased rapidly with decreasing spectral splatter as the onset duration increased. The data show that the errors for 2000-Hz tones increased no faster than for 500 Hz as the onset duration increased from 0 to 50 ms. We think it likely, therefore, that ITD at onset was not a usable cue in our experiment at 2000 Hz. Instead, we suggest that IID cues during the onset were responsible for the successful localization observed at brief onset durations.

E. Experiment 5: Low intensity

The onsets in our experiments have been described in terms of onset duration but we could as readily have used onset rate (level increase per unit time) because these two variables covaried. For example, a 100-ms onset duration always corresponded to an onset rate of 0.5 Pa/s because peak amplitude was fixed throughout at 65 dBA (= 68 dB *re*: $20\,\mu$Pa). In experiment 5 the peak level was reduced to 40 dBA so that a comparison with the standard allowed us to distinguish effects of onset duration from those of onset rate.

1. Method

The subjects, room configuration, and conditions of this experiment were the same as for experiment 4 (high frequency). The stimuli were 500-Hz sine tones with an intensity of 40 dBA.

2. Results and discussion

a. $\overline{D}$, $\overline{C}$, *and* $\bar{s}$. The lowermost panel of Fig. 5 shows that a 25-dB reduction in intensity (relative to the standard) greatly altered the effects of onset duration. It limited the perceptual importance of onsets to the shortest duration tested. Statistics $\langle \overline{D} \rangle$ and $\langle \overline{C} \rangle$ now plateau at an onset of 5 ms whereas, in experiments 1–4, all done at 65 dBA, the plateau was at 50 ms or greater. As in all the other experiments of this series, $\langle \bar{s} \rangle$ was unaffected by onset duration.

The strong dependence of localization accuracy on signal level indicates that the conditions necessary to trigger the precedence effect might better be described in terms of some measure of onset rate rather than onset duration. An appropriate measure may be the increase in sound-pressure level per unit time. The increase in errors for 65-dBA tones as the onset duration increases from 0 to 100 ms (experiment 1) is similar to the increase in errors for 40-dBA tones as the onset increases from 0 to 5 ms. Both of these onset rates are approximately 0.5 Pa/s.

Several lateralization studies speak to the role of onset rate, at least indirectly, in that they vary either signal level with onset duration held constant (Scharf *et al.*, 1976; Moss and Colburn, 1979), or onset duration with level held constant (Elfner and Tomsic, 1968). The dependent variable is the jnd in interaural onset time disparity and, in all cases, it changes quite rapidly as a function of the experimental variable, but never so rapidly as pressure per unit time. There is, however, one study in which onset rate was kept constant, via manipulation of both level and onset duration and the results agree with our own. Abel and Kunov (1983) found that a 200-ms onset rise to a maximum intensity of 80 dB had virtually the same consequences for lateralization as a 25-ms onset rise to 60 dB. The amplitude changes over time are quite similar for these two cases, being 1.0 Pa/s for 80 dB and 0.8 Pa/s for 60 dB.

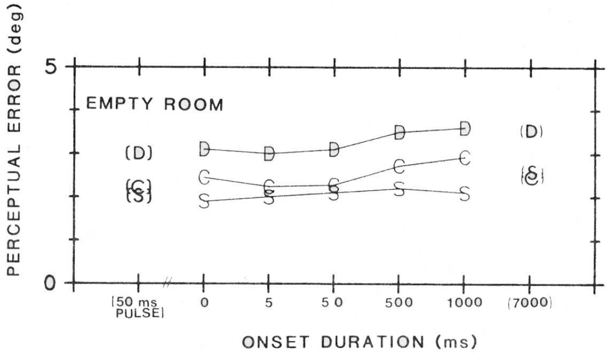

FIG. 6. Errors of localization in an empty, anechoic room. Points connected by the solid lines represent errors for sustained (500-Hz, 65-dB) tones with onset durations as indicated. Points in parentheses give results from paper II, for 50-ms tone pulses, and for sustained tones with 7000-ms onsets.

We conclude that the peak level of a stimulus strongly affects the perceptual importance of an onset cue because the precedence effect depends upon onset rate, perhaps as measured in sound pressure per unit time.

b. $R(k)$. Experiment 5 also permits further comment on misdirection in rooms. The pattern of listeners' constant errors at 40 dB and 500 Hz can be seen in the $\langle R(k) \rangle$ data plotted at the right of Fig. 3. For durations of 50 ms or greater the pattern is very similar to that for 65 dB and 500 Hz shown in the left-hand panel. As expected from the plot of $\langle \overline{D} \rangle$ described above, the long duration limit is reached rather quickly as the onset duration increases for 40-dB tones. We conclude that for asymptotically long onset durations the pattern of misdirection is independent of signal level. For intermediate onset durations (5 and 10 ms in our case) the pattern depends upon level only because higher levels allow the precedence effect to operate at longer onset durations.

F. Experiment 6: Free field

There have been at least two previous attempts to determine the contribution of onsets to the localization of low-frequency tones (500 Hz) in a free field. Perrott (1969) employed the minimum-audible-angle discrimination method of Mills (1958) and concluded that onsets had no importance. Another study was our own, employing the source identification method in an empty anechoic chamber (paper II). We compared subjects' ability to localize 50-ms impulsive tones with their ability to localize sustained tones with slow onsets, and found that the impulsive tones were localized with slightly better accuracy, about 0.5°. Our tentative conclusion was that the presence of an onset improves free-field localization by about that amount. That conclusion had to be a tentative one, however, because our stimuli contrasted in terms of more than just onset. The impulsive tones were much briefer than the slow-onset tones (50 ms versus several seconds) and they included an offset which the slow-onset

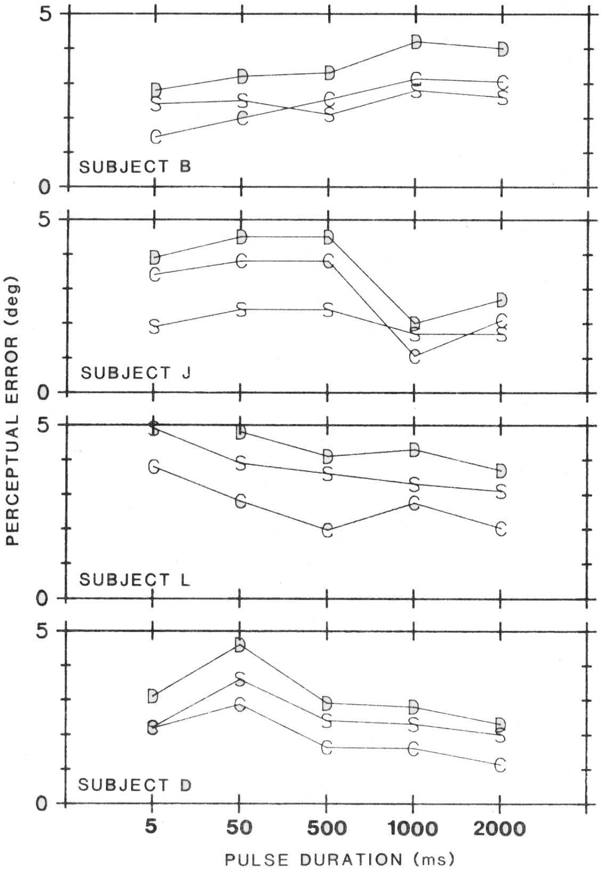

FIG. 7. Errors of localization in a room with a left wall reflection of brief delay, as functions of the duration of a tone pulse. Each panel represents the performance of a different subject.

tones lacked. The empty room experiment of the present study permits a more satisfactory comparison because the tones differed only in their onset.

1. Method

Experiment 6 was conducted in the empty room, with no reflecting surfaces. The stimuli were 500-Hz, 65-dBA sine tones with onset durations of 0, 5, 50, 500, and 1000 ms. All four subjects participated in this experiment for all onset durations.

2. Results and discussion

The error data for this free-field experiment are shown in Fig. 6. Compared to Figs. 2, 4, and 5, the vertical scale has been expanded by a factor of three because errors in a free field are much less than in a room. Also shown in Fig. 6, in parentheses, are the related results from paper II. The two data sets are in reasonable agreement. Both show that 500-Hz tones with abrupt onsets are localized more accurately than tones with slow onsets, the difference being about 0.5°.

III. TONE DURATION

In the experiments of this series we varied the duration of tone pulses and examined the consequences for localization in various rooms.

A. Methods

The stimuli for all of the experiments were 500-Hz, 65-dBA sine tones with rectangular envelopes which began and ended abruptly at sine wave zero crossings. Pulse durations were 5, 50, 500, 1000, and 2000 ms. The subjects of the experiments were the same four who participated in the study of onset duration. Because tones with impulsive envelopes are localized far more accurately in rooms than are slow-onset tones, the vertical scale of figures showing perceptual error is expanded, as for Fig. 6.

B. Experiment 7: Individual results for the WBD room

Experiment 7 was carried out in the standard WBD room. Figure 7 gives the values of $\overline{D}$, $\overline{C}$, and $\overline{s}$ for individual subjects. In the past we have seen evidence of small failures in the precedence effect whenever impulsive tones are localized in rooms (papers I, II). The resulting errors suggested that subjects were being misled by inappropriate IID and ITD cues due to interference effects in the room. It seemed possible, therefore, that an increase in the duration of the tone pulses would lead to an increase in the magnitude of subjects' errors. The data of Fig. 7 show that this occurred for only one subject (B), and no two of the others can be said to have behaved in quite the same alternative manner. The subjects diverge, particularly at the longer duration tones. This may reflect the fact that those tones are long enough to permit a head turn prior to the tone offset. Subjects were free to use the localization strategy they thought most effective, and they reported different choices of strategy. Subject J reported localizing the long tones in two steps, the first to a region cued by the onset and the second to a particular source within that region cued by the offset. Subject B, on the other hand, turned his head continuously, attempting to pick up cues from the steady-state portion of the tones as well as from the onset and offset. Figure 7 shows that the former strategy appears to have been the more effective.

A striking feature of these data is that the error due to misdirection accounts for a much smaller fraction of the overall error than had been the case with the long onset duration tones in experiments 1–5. For subjects L and D the constant error is actually less than the variable error. This reinforces our previous observation that the precedence effect acts mainly to counteract misdirection by the ongoing sound field.

1. Variability in R(k)

The subjects were more consistent with one another in this experiment than in the corresponding experiment done with slow-onset tones (experiment 1). The intersubject variability in $R(k)$ ranged from a minimum of 0.6 at 2000 ms to a maximum of 0.9 at 50 ms. These values are never larger than the smallest intersubject standard deviation seen in experiment 1 (0.9). This close agreement among subjects is probably a consequence of the fact that both an onset and an offset were present in experiment 7 (see Sec. IV below).

C. Experiments 7, 8, and 9: Room effects

The WBD room experiment (experiment 7) was complemented by two others, one in the CBD room with its alter-

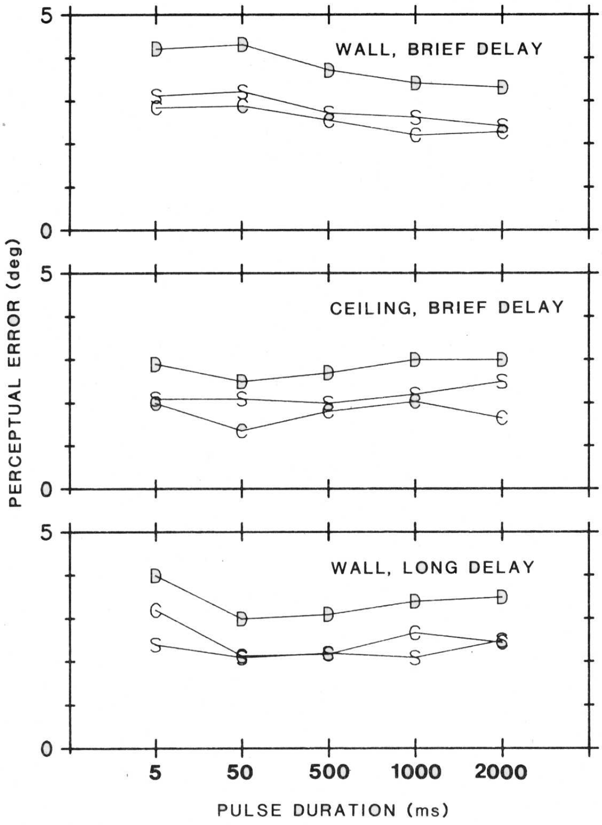

FIG. 8. Errors of localization in a room, as functions of the duration of a tone pulse. Each panel represents the average performance in a room with a particular direction and delay of acoustical reflection as indicated.

native path of reflection, and the other in the WLD room with its increased reflection delay time. The results of all three experiments are summarized in Fig. 8. The average effects of changing the pulse duration were extremely small in each of these rooms, smaller in fact than the individual differences. Whereas the mean difference between the best and worst case in each room was about 1°, the standard deviation in $R(k)$ was nearer to 2°.

Thus a 400-fold increase in the duration of a tone pulse (from 5 to 2000 ms) had no consistent effect on auditory localization in rooms. This result cannot be understood in terms of models of the precedence effect which equate it with binaural inhibition (Blauert, 1982; Lindemann, 1983, 1985), because binaural inhibitory effects do not persist beyond 50 ms (Zurek, 1980). In paper II we proposed the "plausibility hypothesis," which says that subjects discount ongoing cues, after release from binaural inhibition, when those cues are implausible. The present experiments show that the plausibility evaluation operates for durations at least as long as 2 s. This effect may be particularly strong in our experiments because listeners can see the sources. They must coordinate auditory and visual information to derive their responses.

Our result contrasts with the results of several lateralization experiments. Tobias and Zerlin (1959) found, for example, that the lateralization of noise bands improves as the duration increases from 10 to 700 ms. Thus noise bands behave differently from tones, probably because the binaural system regards noise as impulsive and repeatedly resamples with binaural inhibition operating on each sample.

Ebata *et al.* (1968) found that an image lateralized to one side by onset time differences eventually migrated towards a position cued by ongoing interaural time differences. The listening time required for this migration was 180 ms. (See, also, Blauert, 1983, p. 235.) Possibly, migration was observed in these experiments because the ongoing cues were plausible, and not observed in our experiments because ongoing cues in a room are, with high probability, implausible. Alternatively, it is possible that migration effects were not seen in our experiments because the offset transient reinforced the localization cue of the onset transient, though this explanation seems unlikely in view of the accurate localization found in experiments 1–5 for tones with abrupt onsets and no offsets.

IV. TONE OFFSET

The longest duration pulse in experiments 7–9 above (2000 ms) was very much like the abrupt onset tone of experiments 1–6, *plus an offset*. Hence, a comparison across these experiments affords an estimate of the perceptual effects of the offset in our different rooms. The relevant data are presented in Table II. We would highlight the following. (a) Overall, constant, and variable errors for the pulses were always as small as, or smaller than, their counterparts for sustained tones with abrupt onsets. Hence, the presence of an offset never hurt localization and usually improved it. (b) The magnitude of the improvement grew with the magnitude of the errors made on the sustained tones. (c) In all of the reflective environments there was at least some reduction in the constant error whenever a tone had an offset. It therefore appears that listeners can make use of the offset cue, particularly in environments where the interference from reflections is pronounced.

V. CONCLUSIONS

Using the modified source identification method we assessed the importance of tone onset, duration, and offset for azimuthal localization in rooms, and in a free field. Our major conclusions were as follows.

A. Tone onset

(1) A rapid onset facilitates localization in a free field by a measurable but small amount, about 0.5°. It facilitates lo-

TABLE II. Overall ($\langle \overline{D} \rangle$), variable ($\langle \overline{s} \rangle$), and constant ($\langle \overline{C} \rangle$) errors of localization for an anechoic room, and for rooms differing in their directions and delays of acoustical reflection. Results are given for sustained tones with abrupt onsets and no offsets and for 2000-ms tone pulses. The errors are in degrees.

Room	Abrupt onsets only $\langle \overline{D} \rangle$	$\langle \overline{s} \rangle$	$\langle \overline{C} \rangle$	2000-ms pulses $\langle \overline{D} \rangle$	$\langle \overline{s} \rangle$	$\langle \overline{C} \rangle$
Anechoic	3.1	1.9	2.4	2.9	1.9	2.2
Left wall, brief delay	4.6	2.8	3.6	3.3	2.4	2.3
Ceiling, brief delay	3.2	2.5	2.0	3.0	2.5	1.7
Left wall, longer delay	3.9	2.6	2.9	3.5	2.5	2.4

calization in rooms by a substantially larger amount because the onset allows the precedence effect to operate, and without the precedence effect localization is poor due to misdirection cues in the steady-state sound field.

(2) The precedence effect is maximally effective when the signal onset is instantaneous. Its effectiveness begins to diminish as the onset duration is increased, but just when this occurs depends upon the reflection delay time for a room. For those room conditions of the present study having brief delay times (*circa* 1.5 ms), effectiveness began to diminish at something less than 5 ms, the shortest onset duration tested. However, for a room in which there was a long reflection delay (*circa* 9 ms) the precedence effect did not begin to fail until the onset duration reached 500 ms. Models of the precedence effect which hold that it has a summation window of 1 ms or less cannot explain this phenomenon.

(3) Increasing the onset duration beyond the point at which the precedence effect begins to fail results in progressively larger localization errors out to some onset duration beyond which the errors become asymptotically large. We found that this "maximum" duration varied with signal level. A 25-dB decrease in level (from 65 to 40 dB) reduced it by a factor of 20, which suggests that triggering of the precedence effect is determined by some form of *onset rate*, rather than by onset duration. Our data, and those of a previous lateralization study, are consistent with a rate defined as an increase in sound pressure per unit time, e.g., Pa/s.

(4) Vertical reflections are somewhat less detrimental to azimuthal localization than are lateral reflections in every onset condition that we have examined.

(5) As onsets become more gradual, listeners are increasingly misdirected by cues in the steady-state sound field. Different listeners are similarly misdirected by these cues.

(6) The pattern of misdirection reflects a perceptual averaging of acoustical cues over an interval of some tens of milliseconds.

(7) The pattern of misdirection for a room varies with the frequency of a signal but is affected by signal level only in so far as level affects onset rate.

(8) Listeners are able to localize high-frequency tones in a room, probably due to IID cues present in the stimulus onset.

B. Tone duration

(1) Our measurements for the localization of tone pulses of long duration show large individual differences. We attribute these to different listener strategies regarding head movements.

TABLE III. Overall ($\langle \overline{D} \rangle$), variable ($\langle \overline{s} \rangle$), and constant ($\langle \overline{C} \rangle$) errors for impulsive (50-ms) and slow-onset (1-s and 7-s onset durations) 500-Hz tones from the present study and from paper II. Data are reported for rooms with wall and ceiling reflections of brief delay. Errors are in degrees.

		Paper II			Present study		
Room	Stimulus	$\langle \overline{D} \rangle$	$\langle \overline{s} \rangle$	$\langle \overline{C} \rangle$	$\langle \overline{D} \rangle$	$\langle \overline{s} \rangle$	$\langle \overline{C} \rangle$
WBD	Impulsive tone	4.4	2.3	3.8	4.3	3.2	2.9
	Slow-onset tone	9.7	4.4	8.6	9.8	4.6	8.7
CBD	Impulsive tone	3.4	1.9	2.8	2.4	2.1	1.4
	Slow-onset tone	9.7	3.6	9.0	10.4	3.2	9.9

(2) There were no consistent measurable effects of pulse duration on localization in rooms for durations ranging from 5–2000 ms. To account for this result we propose that the precedence effect must be supplemented with a component that we have termed the "plausibility hypotheses" (paper II).

C. Tone offset

(1) The presence of an abrupt offset results in small but measurable improvement in the localization of a long duration tone, especially when the steady-state sound field gives highly inappropriate localization cues.

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APPENDIX: THE MODIFIED SOURCE IDENTIFICATION METHOD

Papers I and II assessed localization in rooms with a source identification method (SIM) having the following features: (1) Subjects faced a horizontal array of eight loudspeaker sources which were separated by four (paper I) or three (paper II) degrees of arc, and numbered *1* through *8* from left to right. (2) On each trial, a sound was presented from one of the sources and the subjects' forced-choice task was to report which one. In previous papers we noted two defects in this method. The first was an end-effects bias: Sources *1* and *8* differed from the other sources in that there was no response alternative bordering them to the outside. The second was that the eight response alternatives together spanned only a small arc. One could imagine that restricting responses to that range might, under certain room conditions, yield rather artificial results. Though inter- and intrasubject consistency tests led us to believe that neither of these methodological limitations posed a serious difficulty in our previous studies, we changed the method for the work described in the present paper to eliminate the formal objections. We called the new method the modified source identification method (MSIM).

The first modification was to expand the source array to 12 speakers. Stimuli were presented from all 12 speakers but we restricted our data analysis to the middle 8 sources to avoid end effects. The second change was to expand the set of response alternatives to cover a full 360° range.

1. Comparisons between the MSIM and the SIM

a. $\overline{D}$, $\overline{C}$, and $\overline{s}$

One way to assess the new method is to compare error statistics for the MSIM with those for the SIM. Table III gives some results for both slow-onset and impulsive tones.

Data for the SIM come from paper II; those for the MSIM are excerpted from corresponding conditions of this study of nearly identical geometries. Comparisons are made for both the wall (WBD) and the ceiling (CBD). The results are remarkably similar, even though the subjects were mostly different in the two studies.

b. $R(k)$

A comparison of $R(k)$ data in SIM and MSIM experiments showed some shifts in reported location for individual sources but the overall pattern remained unchanged. For example, with slow-onset tones and the ceiling we noted a "reversal" of the room in paper II: The more the true location of a source was to the subjects' right, the more it was heard to be to the *left*. The same reversal was present in the CBD data of this study. Likewise, the $R(k)$ functions for slow-onset tones in the WBD room (compare function *8* in Fig. 3 with the "L" function in Fig. 2 of paper II) showed both rightward biases for sources *3, 5,* and *6* (*1, 3,* and *4* in the SIM), and leftward biases for sources *7–10* (*5–8* in the SIM).

2. An analysis of the "outlying" responses

A second way to assess the MSIM is to look at the number and distribution of subjects' "outlying" responses, namely, those responses beyond the range of the source array. We found that subjects were only minimally inclined to choose outliers. In over 20 000 responses, to all kinds of stimuli presented under reflective conditions, subjects chose outliers just 80 times. Three of the four subjects accounted for nearly all of theses responses (each made at least 24 outlying responses), but they did not agree among themselves as to which stimuli and conditions should be heard outside. Of the 80 responses, 72 were for locations less than 15° to either side of the source array, and the most extreme response was just 30° outside the array. It is perhaps noteworthy that the vertical reflecting room produced just one outlier in this study of azimuthal localization while the two lateral-reflection rooms (WBD, WLD) accounted for the remaining outliers roughly in proportion to the number of stimulus presentations per room.

Subjects' reluctance to choose outlying responses may have resulted from the fact that our source array was visible throughout each experiment. This leads us to note, again, the powerful effects that visual information can have on auditory localization (e.g., Thomas, 1941; Warren, 1979). Visual information might limit the perceptual selection from among what would otherwise be equally plausible acoustical alternatives and bias against the choice of alternatives outside the source array.

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[1] Figure 3 shows that $\langle R(k)\rangle$ responses (averaged over listeners) tend to move from one extreme to the other as the onset duration goes through values of 5, 10, and 50 ms. Plots of $R(k)$ for individual listeners, however, often show that responses continue to move toward the long-onset-duration limit for onsets of 100 and 500 ms as well.

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