Localization of sound in rooms IV: The Franssen effect

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The Franssen effect is an illusion that causes human listeners to make large errors in localizing a sound source. This paper describes steps taken to convert the illusion into an experiment in order to study the localization precedence effect as it operates in rooms. The results of the experiment suggest that there are two components to the illusion: The first is the inability of listeners to localize a sine tone in a room in the absence of an onset; the second is the obscuring of modulation cues by the irregular transient response of a room. Experiments show that the Franssen effect fails completely in an anechoic environment, as expected if the effect depends upon the implausibility of steady-state cues in a room. The Franssen effect also fails when the spectrum of the sound is dense.

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INTRODUCTION

Thirty years ago, two-channel stereophony was becoming the standard for electronic sound reproduction. The popular acceptance of this medium provided an impetus for psychoacoustical studies of two-channel listening. Thus, in 1960, there appeared a remarkable thesis by N. V. Franssen on the localization of sounds presented by two loudspeakers. A second report was subsequently published as a book (Franssen, 1962). Informal experiments described in these works made use of a surprising illusion, now known as the Franssen effect (Blauert, 1974; Berkley, 1987).

A. The Franssen effect—F1

The Franssen effect in its original version, to be called version F1, is created with two loudspeakers in front of a listener: one to the left of midline, the other to the right. A sine tone with a sharp onset is sent to one loudspeaker, for example the left, as shown in Fig. 1(a). Immediately after the onset, this tone begins to decay exponentially, with a time constant t, while a similar sine tone begins to rise at the right loudspeaker, increasing with a time constant also equal to t. The signals to left and right speakers are thus complementary: Their sum is a sine tone with a rectangular onset envelope. The transient part appears at the left and the steady-state part appears at the right. The tone continues to sound from the right loudspeaker for an arbitrary length of time and is then turned off. On turnoff, the tone in the right speaker decays exponentially while a complementary transient signal (out of phase with the tone at the right) appears in the left speaker so that the sum of the right and left speaker signals is zero. Therefore, the offset of the sum of the signals is also rectangular.

Using this stimulus, Franssen found that a listener hears the entire stimulus as coming from the left speaker only. The listener is unaware that the right speaker has ever sounded, even though it is the right speaker that has been on for most of the time. This is the Franssen illusion.

Franssen's informal experiments demonstrated the illusion for time constants (transition durations) t ranging from 20–40 ms and for full-on durations ranging from 250–4000 ms. As the angular separation between the sources increased, the illusion was less successful. The illusion failed when the loudspeakers were replaced by headphones, which was regarded as a case of extreme angular separation between the sources.[1]

Franssen explained his illusion as the result of a particular emphasis given to onsets by the auditory system. He developed a delay-line model of the binaural hearing system, incorporating peak detection and contralateral inhibition. An interaural time-intensity trading was automatically included in the model as were time constants for establishing and releasing contralateral inhibition. The model particularly featured the inhibition of steady-state location information by onset transients. It thereby attempted to account for the illusion using a model of binaural interaction.

Within a decade, however, it had become clear that Franssen's illusion cannot be understood entirely on the ba-

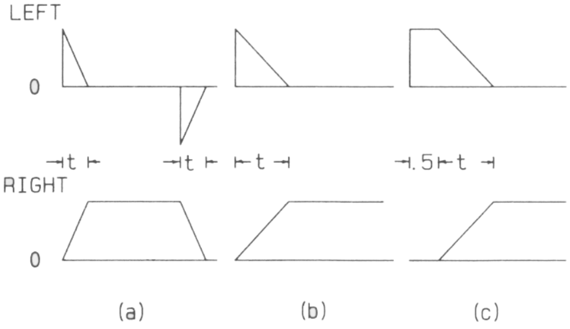

FIG. 1. Envelopes for the signals from left and right sources in the Franssen effect experiments: (a) Experiment F1; the negative envelope is intended to indicate a phase reversal of the signal; (b) experiment F2; and (c) experiments F3 and F4.

sis of binaural interaction. Instead, the illusion probably has something to do with the effect of room acoustics on sound localization (Blauert, 1974). The Franssen effect may be regarded as a dramatic illustration of the precedence effect, wherein the signal received directly by a listener entirely dominates signals that are reflected from walls in determining the perceived location of the sound source.

B. The Franssen effect—F2

A second version of the effect was presented by Berkley in a demonstration in 1983. This version, called F2, is shown in Fig. 1(b). It begins just like version F1. A sine tone is turned on abruptly at the left speaker, then faded out to zero while a complementary tone is faded in at the right speaker. The tone at the right continues to sound indefinitely. Berkley used a transition duration of 15 s. In this illusion the listener believes that the left speaker continues indefinitely, even though the left speaker is completely off. This was successfully demonstrated in a large hall to an audience of several hundred. Illusion F2 is similar to F1 in that the sound source always seems to be at the location of the transient. However, it is inconceivable that illusion F2 is the result of neural inhibition in the auditory system. The experimental transition duration is much too long.[2]

C. The precedence effect and the plausibility hypothesis

The present interest in the Franssen effect derives from previous work on the azimuthal localization of sound in rooms (Hartmann, 1983; Rakerd and Hartmann, 1985, 1986). Azimuthal localization for sounds mainly in the forward direction can be understood as a neural computation based upon some weighted combination of interaural time differences and interaural intensity differences (Shaxby and Gage, 1932; Mills, 1972; Durlach and Colburn, 1978). Considerable attention has been paid to trading relationships between these two kinds of interaural differences (e.g., Hafter and Carrier, 1971).

Our 1985 study on the localization of sine tones having no onset transients suggested that, in a room, a listener subconsciously reweights steady-state interaural differences according to their plausibility. This idea was called the "plausibility hypothesis." The hypothesis says that the listener does not know how to compensate for the effects of room reflections in the localization of sounds without onsets. This is held to be true even if the listener is familiar with the sound and with the room. Instead, the listener is supposed to respond to interaural cues as though all sounds were direct, i.e., as though the sounds were heard in a free field. But for a sine tone of given frequency in a free field certain interaural cues are impossible. As a result, certain interaural cues that actually do occur in rooms assume the status of implausible and, according to the plausibility hypothesis, are discounted.[3]

It was proposed that the discounting of implausible steady-state cues is an important contribution to the precedence effect as it operates in rooms. If the Franssen effect manifests the precedence effect, then it too depends upon implausibility. From the above reasoning, the 1985 paper predicted that, in an anechoic room, where all cues are necessarily plausible, the Franssen effect will fail. A second prediction that might be made is that the Franssen effect will fail, even in a reverberant environment, if the sine signal is replaced by a signal with a dense spectrum such as noise. In both cases, a listener can reliably localize the sound without the onset transient. To test these predictions, we performed the experiments described below.

I. FRANSSEN EXPERIMENT F2

A major problem in this study was to devise experiments to obtain meaningful data on an effect that is essentially an illusion. In general, illusions are difficult to maintain with practiced subjects because subjects learn to use cues that naive observers of a demonstration do not. In the case of the Franssen effect, cues relating to the diffuseness of the sound image, as opposed to localization of the image, are present (Blauert, 1974). There are additional cues from the time-varying pattern of interference between the two sources.

A. Method

Our experimental method was to present listeners with tones, some of which involved a transition from one source to another, as in the Franssen illusion F2, and some of which did not. We reasoned that, if a strong Franssen effect is present, the listener could not tell the difference between these. Accordingly, there were four kinds of trials: LR, RL, LL, and RR. On an LR trial, the signal was turned on with an abrupt onset at the left source, which was then faded out as the right source was faded in. The right source remained on until the listener made a response. Then, it was faded out with a time constant of 0.5 s. On an LL trial, the signal was turned on at the left source and it remained on until the listener made a response. Experimental trials were presented in runs. During a run, all the experiment parameters remained constant. A run consisted of 72 trials, 18 trials of each of the four kinds in random order.

B. Stimuli

The two sound sources (left L and right R) and the listener's head were at the vertices of a horizontal equilateral triangle. Therefore, the source separation was 60 deg. The sides of the triangle were either 10 ft (3.0 m) or 20 ft (6.1 m).

Each source was actually a cluster of six loudspeaker drivers (Minimus 3.5). When sound was required from the left (right) source, one of the six left (right) speakers, connected at random by a computer-controlled relay bank, was activated. This procedure prevented listeners from identifying a source by coloration of the tone onset associated with a particular speaker. The speakers of a single cluster spanned 2 deg of horizontal arc and 3.8 deg of vertical arc at a distance of 10 ft; they spanned half those angles at a distance of 20 ft. The speakers were arranged radially with respect to the listener so as to span almost a full wavelength at 500 Hz. Therefore, the interference pattern between the direct sound from a given source and reflections from room surfaces was somewhat randomized from trial to trial.

Signals were 500-Hz sine tones shaped by computer-controlled amplifiers. In a typical transition trial, e.g., LR, the amplifier connected to the left source was turned on abruptly and the transition immediately began, with the left source decaying and the right source rising in a complementary way. The transition ramps were linear in amplitude versus time. Four different transition durations were used: 20, 80, 1000, and 4000 ms. The levels of the signals were randomized by ± 1 dB from trial to trial about a mean of 60 dB, as measured with a sound-level meter at the position of the listener.

C. Rooms

Three rooms were used in this experiment. The first room was an anechoic room, $11 \times 15 \times 8$ ft high ($3.4 \times 4.6 \times 2.4$ m), IAC number 107840. Only the 10-ft distance was possible in this room. The second room, called the "laboratory," was 28×24 ft with a 15-ft ceiling ($8.5 \times 7.3 \times 4.6$ m). The walls were concrete block, the ceiling was concrete, and the floor was covered with vinyl tile. The third room was a reverberation room, IAC number (also) 107840, 25×21 ft with a 12-ft ceiling ($7.7 \times 6.4 \times 3.6$ m).

To parametrize the listening conditions, we measured the ratio of the total sound power to the direct sound power (T/D) for each room and distance, as described in the Appendix. For the anechoic room, the ratio was 1. For the laboratory, the ratios at 10 ft and 20 ft were, respectively, 7 and 19. For the reverberation room, the ratios at 10 ft and 20 ft were, respectively, 32 and 82.

D. Subjects

There were five subjects, B, J, S, W, and Z, four males and one female, all with normal hearing according to their own reports. Subjects B and W were the authors.

E. Procedure

Each subject (5) did one run (72 trials) for each value of the transition duration (4) in each environment (5). The experiment was self-paced. After the stimulus transition was complete, or an equivalent time had elapsed for a trial without a transition, two small lamps, one on each source, were lit to request a response. The listener then pressed in succession two buttons, marked L and R, on a response box. Allowed responses were LR, RL, LL, and RR according to the listener's perception of the location of the initial part and the final part of the stimulus tone. The lamps were blinked briefly whenever the computer detected a button press. If the listener became confused, he had the option of pressing both buttons simultaneously. In that case, the computer canceled responses to the last one or two or three trials (determined randomly) and began the trial sequence again from that point. Each run therefore had exactly 72 forced-choice trials, 18 of each kind. There was no feedback.

F. Data reduction

The data can be described by a confusion matrix, as in Table I. Here, the rows correspond to the stimuli, LL, LR, RL, and RR. The columns correspond to the responses. A perfect performance for a single run is indicated by 18 in each of the diagonal positions in the matrix and zeros everywhere else.

TABLE I. The confusion matrix and its interpretation in terms of the variables of signal detection theory. Hit: transition (LR or RL) correctly identified; miss: transition missed; CR = correct rejection: correct response to no transition; FA = false alarm: response that a transition occurred when it did not; MO = missed onset: first source incorrectly identified.

		Response			
		LL	LR	RL	RR
Stimulus	LL	CR	FA	MO	MO
	LR	miss	hit	MO	MO
	RL	MO	MO	hit	miss
	RR	MO	MO	FA	CR

1. Missed onsets

If the listener always correctly identifies the first source, with its sharp onset transient, the 4×4 confusion matrix becomes a pair of 2×2 matrices on the diagonal. Nonzero entries in the off-diagonal 2×2 matrices correspond to incorrect identification of the first source. Such missed onsets occurred very rarely in our data, less than 1% of all the responses. There were so few missed onsets that it is fair to ignore trials on which they occurred.[4]

2. Hits, misses, correct rejections, and false alarms

If missed onsets are ignored, then the experiment becomes isomorphic with the traditional yes/no experiment, much studied in terms of signal detection theory (Green and Swets, 1966). Here, we suppose that a stimulus source transition (LR or RL) corresponds to the presence of a signal. A "hit" occurs when the listener correctly identifies such a transition. A "miss" occurs when the listener responds that no transition has taken place when, in fact, it has. For a "correct rejection," the listener correctly identifies a trial when there has been no transition (LL or RR). For a "false alarm," the listener says that a transition has occurred when, in fact, no transition has taken place.

If the Franssen effect operates perfectly, then all responses to transition trials (LR or RL) would be misses (responses LL or RR, respectively). There is no particular prediction for nonsignal trials. Thus the presence of the Franssen effect would be indicated by poor performance in our task because the hit rate would be low. Good performance should be interpreted as evidence that the Franssen effect is failing. For intermediate performance, a reasonable criterion is that the illusion fails if d' is greater than 1.

To illustrate the method of data reduction, Table II shows the results of a typical run. The sum of all entries in a row is 18 as it must be. There is one missed onset. (It is not typical to have as many as one per run.) There are $1 + 2 = 3$ false alarms for a false alarm rate of $3/36 = 8.3\%$. There are $7 + 5 = 12$ hits for a hit rate of $12/35 = 34.3\%$. (The denominator is reduced by 1 here because of the missed onset.)

TABLE II. The confusion matrix shows the number of responses of each type for each type of stimulus. There were 18 stimuli of each type in an experimental run. The data are from a typical run in a reverberant environment.

		Response			
		LL	LR	RL	RR
Stimulus	LL	17	1	0	0
	LR	10	7	0	1
	RL	0	0	5	13
	RR	0	0	2	16

As usual, the sum of the hit rate and the miss rate is 100%. The sum of the false alarm rate and the correct rejection rate is 100%. The value of d' corresponding to these hit and false alarm rates is 0.98.

G. Results

The results of the F2 experiment are shown in Fig. 2 for each of the five listeners. The horizontal axis gives the T/D ratio (the ratio of total sound power to direct sound power) on a logarithmic scale; the vertical axis shows the resulting value of d'. Results for transition durations of 20 and 80 ms (short) have been combined in Fig. 2(a); results for 1000 and 4000 ms (long) have been combined in Fig. 2(b).

What is most obvious in the figure is that performance was excellent in the anechoic room ($T/D = 1$.) The average hit rate was 98.5; there were no false alarms in the 720 trials having no transition. The conjecture based upon the plausibility hypothesis is thereby verified. The Franssen effect fails in an anechoic room. Futhermore, there can be no remaining doubt about the importance of room acoustics for the existence of the Franssen effect.

Comparing Figs. 2(a) and (b) shows that, for environments that are not anechoic, there is a strong effect of transition duration. For short durations, there are only two data points (out of 20) with d' greater than 1. For long durations, there are only four data points (of 20) with d' less than 1. An analysis of variance verifies that average performance for long durations is significantly better than performance at short durations, $F(1,4) = 23.3, p < 0.009$. The conclusion is that, for short transition durations, the Franssen effect occurs; for long transition durations, the effect fails.

It is very hard to understand the above comparison based only on what we know about sound localization in rooms. To the extent that transition durations matter at all, one would expect better localization performance for short transitions where the onset of the second source is more abrupt (Rakerd and Hartmann, 1986).

We conjectured that the good performance seen in experiment F2 at long transition duration actually has little to do with localization *per se*. Instead, we suspected that listeners used modulation cues to perform the task. When one source is decaying and the other is rising, an interference is generated that may lead to a maximum or minimum in sound level as a function of time. Listeners can hear this interference as a loudness modulation and use it as a cue that a transition has occurred. In addition, there may be a changing pattern of diffuse location of the sound. The sound image may change from one that is broadly distributed and centered on some highly implausible location to one that is differently distributed and centered on some other highly implausible location.[5] By contrast, when there is no transition, the sound remains constant in all its aspects. We further conjectured that these modulation cues are available to listeners only if the transition duration is long compared to the buildup time for the sound field in the room. Only then can listeners distinguish between the modulation due to a source transition and the temporal fluctuations that accompany the onset of a sound in a room. These conjectures could account for the results of the F2 experiment; namely, performance was good for long transition durations but poor for short transition durations. To test the conjectures, we performed several other experiments.

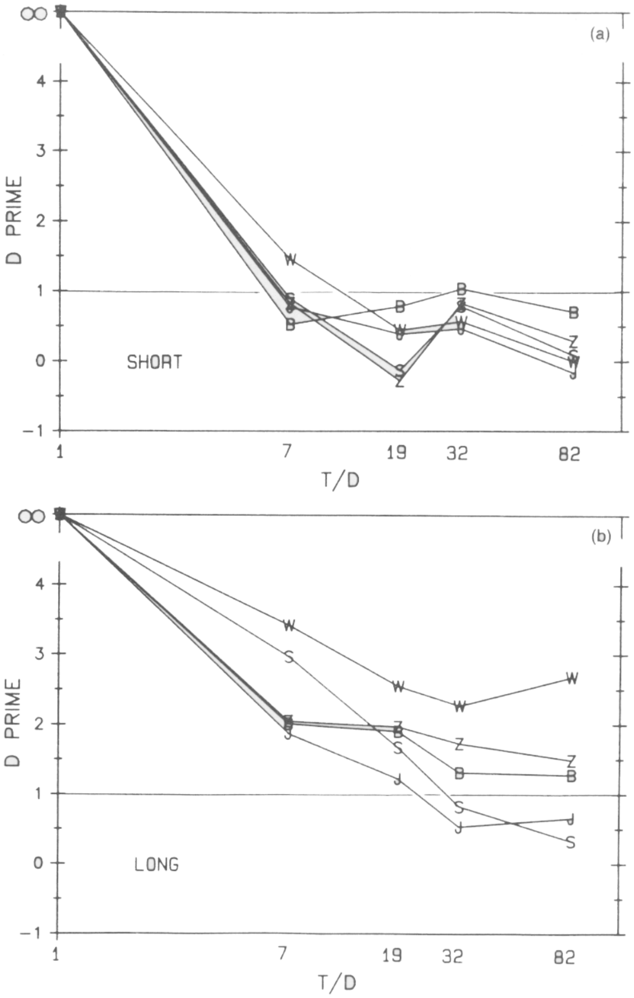

FIG. 2. Results for experiment F2. The horizontal axis shows the total-to-direct sound power ratio on a log scale. The anechoic environment corresponds to $T/D = 1$. From left to right other environments are: laboratory at 10 ft, laboratory at 20 ft, reverberation room at 10 ft, and reverberation room at 20 ft. The values of d' indicate the performance in each condition: (a) "Short" combines data for 20- and 80-ms transition durations and (b) "long" combines data for 1000 and 4000 ms.

II. FRANSSEN EXPERIMENT F3

The F3 version of the Franssen effect was created specifically to eliminate confusion between sound buildup in a room and the transition among sources.

A. Method

The stimulus for Franssen F3 was identical to Franssen F2 except that the transition (when it occurred) did not occur immediately after the onset of the first source; instead, there was a 500-ms delay before the transition, as shown in Fig. 1(c). It was expected that this delay would allow the sound from the first source to stabilize so that any modulation heard afterwards must be due to a transition. We predicted then that performance would be good for both short- and long-transition durations.

The procedure for experiment F3 was identical to F2, except that no runs were done in the anechoic room.

B. Results

The results for the F3 experiment are shown in Fig. 3(a) and (b); these are directly comparable to Fig. 2(a) and (b). As expected, performance in F3 is good; all values of *d'* are greater than 1. In contrast to F2, there is no tendency for better performance at long transition durations; in fact, the reverse is true. Apparently, the abrupt modulation resulting from short transitions was more easily detectable than the slow modulation from long transitions. It seems possible that very-long-transition durations, e.g., 15 s as used by Berkley, might make weak modulation cues even harder to detect.

Figure 3 also shows that there is little systematic dependence of *d'* on the ratio *T/D*. Rather, there seem to be erratic differences in the way that individuals learned to identify transitions in the various environments. Despite this irregularity, the overall performance was good, and one can conclude that the Franssen effect F3 fails in all environments. Figure 3(b) is rather similar to Fig. 2(b), suggesting that for long-transition durations listeners used the same cues in both experiments F3 and F2.

III. FRANSSEN EXPERIMENT F4

The stimulus of experiment F3 delayed the transition to make it distinct from the room transients. This made the modulation cues more apparent and more effective. Experiment F4 was designed to do the opposite, to make the modulation cues useless. The intention in this case was to cause listeners to rely exclusively on localization cues.

A. Method

In experiment F4, there was an interference pattern on every trial, including trials with no source transition. This was done by using a transition among loudspeakers on every trial. On an LL trial, for example, one speaker of the left source was faded off while another speaker of the left source was faded on. Because of the radial distribution of the speakers of each source, intensity modulation did occur on almost all of the trials where no source transition occurred. The speaker control logic allowed for 72 different kinds of transition from one speaker to another, too many for a listener to learn to recognize modulation patterns. Each kind of transition was used once in an experimental run. The stimulus and room conditions were otherwise identical to those of experiment F3 except that an anechoic condition was included in F4.

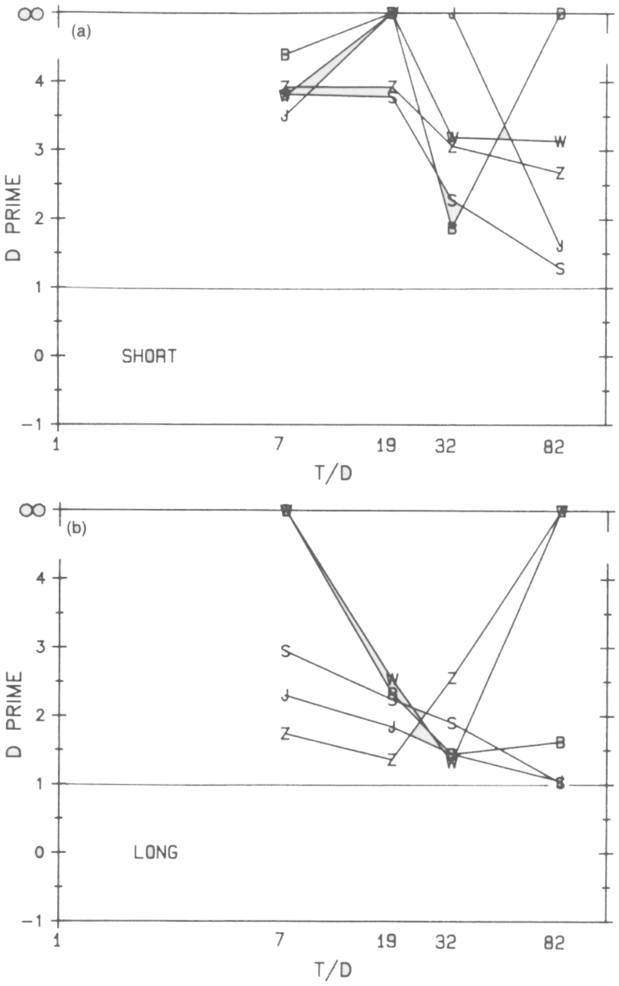

FIG. 3. Same as Fig. 2, except that the data are for experiment F3.

B. Results

The results of experiment F4 are given in Fig. 4(a) and (b). Again, it is evident that the Franssen effect fails dramatically in the anechoic room. In other environments, the Franssen effect appears to work rather well. Only for the smallest value of the *T/D* ratio is the value of *d'* greater than 1 for most of the subjects.

The data for short-transition durations [Fig. 4(a)] closely resemble the data for short-transition durations in experiment F2 [Fig. 2(a)]. This is evidence that the obscurring of modulation cues for short transitions caused subjects in experiment F2 to rely on localization cues. Also apparent in Fig. 4 is that performance in experiment F4 did not depend upon the transition duration. Figure 4(a) and (b) for short and long durations are very similar. A more detailed study of duration dependence showed that neither hit rates

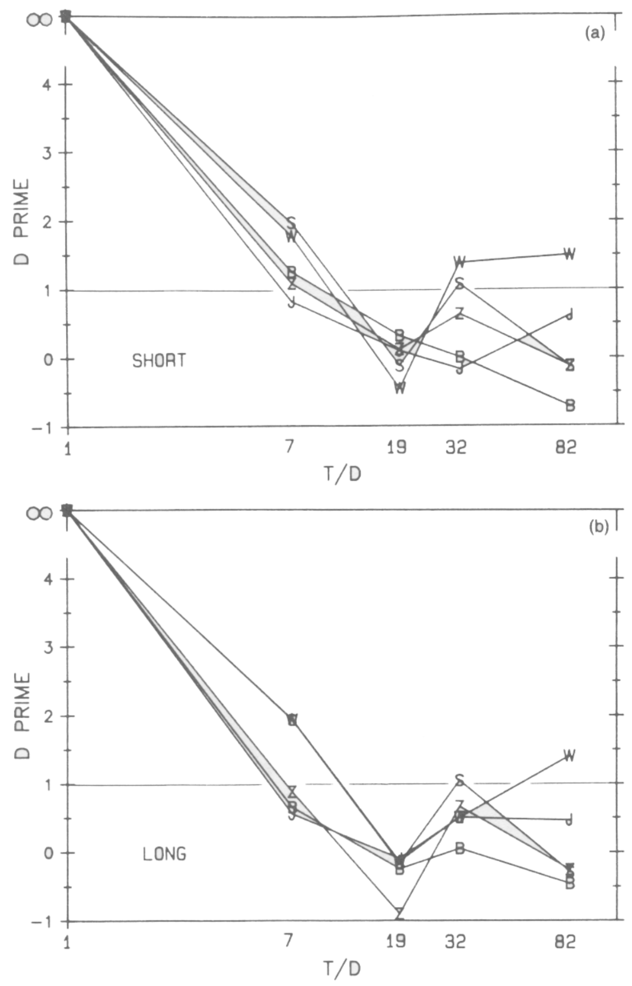

FIG. 4. Same as Fig. 2, except that the data are for experiment F4.

nor false alarm rates varied significantly with transition duration in any environment.

In experiment F4, there were 14 cases of negative *d'*. That means that having correctly identified the location of the first source, the listener would have done better by reversing his judgments as to whether a transition took place or not. Negative *d'* values tended to occur at the 20-ft distance; possibly, there is an acoustical reason for this result, but we did not try to find it.

IV. EXPERIMENTS F2 AND F4 WITH NOISE

While experiments F2 and F4 were set up for the sine tone experiments, we also tested the conjecture that the Franssen effect would fail for noise signals. This conjecture was suggested by Hartmann's (1983) observation that spectrally dense signals can be successfully localized in a reverberant space even if there is no onset transient.

A. Procedure

The noise experiments were done in the laboratory room, F2 at 10 and 20 ft, F4 at 20 ft. The noise was low-pass filtered at 14 kHz (−96 dB/oct) and presented at 60 dB SPL, as measured from the listeners' position. The experiments were otherwise identical to experiments F2 and F4.

B. Results

The results of the noise experiments were the same for experiments F2 and F4: *d'* values were very large, with an average hit rate of 98% and an average false alarm rate of 1%. This did not depend upon transition duration, nor upon distance, nor upon subject. The results are conclusive: The Franssen illusion fails for noise stimuli.

V. THE ENVIRONMENT

We chose to characterize the experimental environments by the ratio of total sound power (= direct plus reverberant) to direct sound power. Figures 2 and 4, which show the degree to which the Franssen effect fails, have been plotted with this ratio as the independent variable. Apart from the obvious systematic behavior when the ratio is 1 (anechoic conditions), it appears that the data do not vary monotonically with this ratio. Only in Fig. 2(b) do the values of *d'* seem to decrease monotonically with increasing ratio, but it is in this case that we believe that listeners used modulation cues instead of localization cues.

For the three cases shown in Figs. 2(a), and 4(a) and (b), where we believe that listeners used localization cues, the values of *d'* seem to depend primarily on the source-to-listener distance and only secondarily on the total-to-direct sound power ratio. The reader can check this by mentally reversing the data points with T/D values of 19 and 32. That puts the two 10-ft conditions to the left of the two 20-ft conditions. Then, the data seem to vary more nearly monotonically with the independent variable. In our geometry, the sources and listener were near the center of the room for the 10-ft condition. In the 20-ft condition, both sources and listener were near the walls. This result leads us to conjecture that good performance occurs when early reflections from the walls of the room are delayed compared to the direct sound. We suspect, therefore, that, if the sources and the listeners were placed in the middle of a room with a large volume the Franssen effect might well fail, even though the reverberation time and the total-to-direct sound ratio are both large.

VI. CONCLUSIONS

We have studied the Franssen effect in three different rooms: in an anechoic room, in a laboratory, and in a reverberation room. Among these rooms the ratio of total-to-direct sound power varies considerably. We further varied this ratio by putting listeners at two different distances from the sound sources, 10 and 20 ft.

Our experiment required listeners to detect a transition from one source to another. The data could be reduced to terms of hit rates and false alarm rates. Strictly interpreted, the Franssen effect occurs if the hit rate is exactly zero. That, however, is an unreasonable demand to make of experimental data. It is more reasonable to say that the Franssen effect is observed if the value of d' is less than unity, and that it fails if the value of d' is rather greater than unity.

The experiments showed unambiguously that the Franssen effect fails in an anechoic environment, as predicted by the plausibility hypothesis. In anechoic conditions, the steady-state localization cues are both adequate for localization and plausible, hence not discounted.

Experiments also showed that the Franssen effect fails for a noise stimulus. This failure merits some comment because Franssen himself found that the illusion was successful for complex tones, specifically for half-wave-rectified sines. We think it possible that both our results and Franssen's are valid. The apparent contradiction may be attributable to the different spectral densities. Noise is very dense; a half-wave-rectified sine is not dense because all odd harmonics, except for the fundamental, are absent from the spectrum. The significance of spectral density is that Hartmann's (1983) study of signals without onset transients suggested that localization performance improves monotonically with increasing spectral density. Because the Franssen effect appears to depend upon an inability to localize the steady-state sound, it is possible that it works for rectified sines but fails for noise.

We found four other conditions where the Franssen effect failed, with hit rates of 80% or greater. These were the conditions of experiment F3 where the listener was encouraged to use modulation cues to do the task. The data from the F3 experiment, as shown in Fig. 3, appear rather erratic. However, if the data are averaged over transition durations and over subjects, the hit rate decreases and the false alarm rate increases regularly as the ratio T/D increases. This behavior resembles that of experiment F2 for long-transition durations [Fig. 2(b)], the other case where we suspect that listeners used modulation cues to do the task.

In summary, we conclude that the Franssen effect owes its success primarily to the inability of listeners to localize a sine tone in a room when there is no onset transient. To study the effect experimentally, however, one must take steps to eliminate modulation cues. Modulation cues can be eliminated by using a short-transition duration or an environment with a very large total-to-direct sound power ratio, or both. Alternatively, modulation cues can be rendered useless by an experiment of the form of F4, where modulation is present on every trial. A less satisfactory alternative would be to use naive observers whose tendency to try to localize the sources causes them to miss the modulation cues.

As to localization itself, a sine tone without an onset transient does lead to localization cues, both interaural time differences and interaural intensity differences. However, in a room, these cues are, with high probability, implausible. The plausibility hypothesis postulates that implausible localization cues are discounted by a subconscious process, and in the case of the Franssen illusion are overridden by the highly plausible localization cues in the onset of the first source. Although the experimental evidence is not strong, it appears (Figs. 2 and 4) that the implausibility of localization cues may depend more upon the geometrical details of source positions, room surfaces, and the listener's position than it does upon the total-to-direct sound power ratio.

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APPENDIX—ROOM MEASUREMENTS

Room conditions for the experiments above were characterized by a ratio of total sound power (= reverberant plus direct) to direct sound power. This appendix describes how the measurements were made.

First, the direct sound power was determined by measuring the sound-pressure level in the anechoic room for each of the 12 loudspeakers in the two source clusters. The clusters were arranged as in the psychoacoustical experiments, and the microphone of a remote-reading Larsen–Davis sound-level meter was at the position normally occupied by a listener's head, 10 ft from each cluster and 47 in. from the wire-grid floor. The signals were 500-Hz sine tones, as in the psychoacoustical experiments. The direct sound power for a distance of 20 ft was taken to be one-fourth of that measured at 10 ft.

The next step was to measure the total sound power, at the position of the listener, for the various room conditions: laboratory room at 10 and 20 ft and reverberation room at 10 and 20 ft. Because of standing-wave effects, it was necessary to do a spatial average, over a minimum span of one wavelength, as recommended by Beranek (1954). In fact, our procedure was a double average, one over source positions and the other over receiver positions. The average over source positions was done by using the 12 speakers of the source clusters with the same drive level as in the anechoic room measurements. The average over receiver positions was done by placing the measuring microphone at 16 different locations, uniformly distributed on a 2- × 2-ft grid, in the horizontal plane.

The sound-level readings, as measured in a given room condition for a given speaker, were converted to power, then averaged over the 16 microphone positions, and then divided by the direct sound power for that speaker to find a total-to-direct sound power ratio. The ratios for the 12 speakers were then averaged to find a total-to-direct ratio for the given room condition. The ratio for the anechoic room is unity by construction; the ratios for the other four room conditions varied from 7.2 to 82.0, as noted in the text above.

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[1] Another headphone analogy to the Franssen experiment that did not produce the illusion was done by Ebata *et al.* (1968), experiment 4. These authors even found what might be called an "anti-Franssen" effect: The lateralization of an offset click was biased in the direction of a steady-state sound.

[2] Effect F2 differs from F1 in that F1 has an offset and F2 does not. This difference is probably of very little importance because an offset that has the same azimuth as the onset seems to contribute minimally to the localization of a sine tone (Rakerd and Hartmann, 1986).

[3] Impossible cues include large interaural intensity differences at low frequency and interaural phase differences that are incompatible with head dimensions. Perhaps included are contradictory cues, such as the compensating time and intensity cues used in trading experiments. Auditory cues

that are incompatible with source positions as seen visually might also be regarded as impossible.

[4] The smallest percentage of missed onsets occurred in the anechoic room, three such responses out of 2880 trials. For the sine tone stimulus in the laboratory and in the reverberation room, the number of missed onsets at a distance of 20 ft exceeded the number at a distance of 10 ft by a factor of 3, 1% vs 0.3% (8640 trials each). The rate of missed onsets was the same in the laboratory and reverberation room, 0.7%. Apparently, the missed-onset rate depends more upon experimental geometry than it does upon the ratio of total-to-direct sound. There were so few instances of missed onsets that they are neglected in the further analysis of the data.

[5] Before doing experimental runs, the listeners were informed in some detail about the nature of the stimuli. In particular, they were told that in some cases it might be to their advantage to ignore localization cues and to concentrate instead on modulation cues. Informal experiments with listeners who were not informed about modulation found that some listeners quickly learned to use modulation cues and others did not. Therefore, the performance data fell into two rather distinct ranges.

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Shaxby, J. H., and Gage, F. H. (**1932**). "The localization of sounds in the median plane: An experimental investigation of the physical processes concerned," Medical Research Council of Britain, Special Rep. 166 (Present-day readers should understand that "median plane" means "sounds in the horizontal plane.")