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Frequency-Response Characteristic of Auditory Observers Detecting Signals of a Single Frequency in Noise: The Probe-Signal Method*

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Four experiments were conducted to develop and test a method of determining the frequency-response characteristic of the observer when he listens for single-frequency signals presented against a continuous background of wide-band noise. After observers were trained to detect primary signals of a single frequency, probe signals of various other frequencies were presented infrequently, in lieu of the primary signal. Primary signals and all probe signals were presented with very similar amplitudes that would be expected to render them all equally detectable if presented alone in single-frequency experiments. Estimates of the detectability of the signals of the various frequencies were obtained concurrently in a two-alternative forced-choice procedure. The results from 14 observers were quite similar and show differences in detection as a function of signal frequency when the primary signal was of 1000 or of 1100 Hz. In general, the primary signal was correctly detected 75%–90% of the time while signals with frequencies at approximately 150 to 200 Hz on either side of the primary-signal frequency were detected at the chance level, 50% correct. In as few as three experimental sessions, the observer's frequency-response characteristic was obtained using the probe-signal method.

INTRODUCTION

THE detection of auditory signals is degraded by the addition of a background of noise. The human observer probably could perform best in such a listening situation if he could select from the total auditory input that portion that best represented the signal. If the signal is always of the same frequency, experience with the task could inform the observer that one basis for selection would be along the frequency dimension.

For some auditory situations, a filter has been useful as a model of the selection being performed by the observer (Broadbent, 1958; Green and Swets, 1966; Schafer *et al.*, 1950; Sherwin *et al.*, 1956). For example, after having detected signals of a single frequency for some time, observers have shown drastically reduced detection of other signals of equal energy but of different frequency (Tanner, Swets, and Green, 1956; Karoly and Isaacson, 1956; Greenberg, 1962). The observer behaves as if operating with a narrow-bandpass filter tuned to the frequency of the signal he had been detecting. The studies to be reported here were designed to develop and test a method of obtaining a direct, behavioral measure of the frequency selection performed by the observer who is detecting signals of a single frequency presented in wide-band noise.

I. PROBE-SIGNAL METHOD

A. Rationale for the Method

As a model of the observer's selection process, we assume a bandpass filter centered on the frequency of the signal and attenuating frequency components of the input on either side of that signal frequency. As an exemplar for our method, we used the technique that an engineer may employ to measure the frequency-response characteristic of an electronic filter device. After setting up his filter, he could insert into the device various test signals, or probe signals, of different frequency but of equal energy, one at a time. The frequency-response characteristic of the device is then the relative output of the filter as a function of the frequency of the input. We desired an analogous procedure that would "set up"

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our observer to listen for the single frequency and to select from his input in a manner suitable to the task. Then, by inserting probe signals at frequencies other than that for which he had been set up to listen, we could evaluate the relative output of the observer as a function of the signal frequency.

One aspect of the procedure that would not trouble the engineer was a potential problem for us. The engineer would be dealing with a passive device that would maintain its characteristic regardless of the nature of the probe signals. However, we could not assume that the human observer would respond passively to the insertion of probe signals. For example, the human observer might perform like a tracking-filter device, altering the placement and/or frequency-response characteristic of the filter in response to a change in the signal frequency.

Some empirical observations and statements from hypothetical models are relevant to this problem. We are concerned with two listening conditions. In what we have been calling the single-frequency condition, the observer is asked to detect signals he knows will always be of the same frequency. In the other condition, that we call the disparate-frequency condition, the observer is told that the signals presented will not always be of the same frequency but will be the same otherwise. It has been demonstrated that if the disparate frequencies are separated sufficiently, detection performance will be poorer than during the single-frequency condition (Green and Swets, 1966).

Some hypothetical models have proposed, in effect, that this performance decrement reflects the form of the observer's selection process (Green and Swets, 1966). Such a process could be fixed; but in surveying the evidence, Swets (1963) suggests that the process may be subject to the control of central factors, or higher centers of the central nervous system. In this way, the process might be altered in its form, or adapted, by the observer to be appropriate to the specific listening condition.

If the selection process is adaptable, we can assume the observer purposefully changes the process. For example, if the decrement observed during the disparate-frequency listening condition reflects an altered selection process, the different forms of the process that the observer adopts must be appropriate or somehow suitable to the different conditions. If an observer adopts a form of selection process suitable for detecting signals of a single frequency, it would appear that before he would alter that process, he would need some information or an "awareness" that his form of the process is no longer suitable to the task. In experiments comparing performance during the single-frequency and the disparate-frequency conditions, the observers are commonly informed of changes in the listening conditions. One could argue that before the observer would change his selection process, he would need to be informed, or be "aware," that such a change would be appropriate.

We have no way of knowing *a priori* that the presence of the probe signals would not in some way inform the observer that the signal would be of two or more disparate frequencies. Because we had set as our goal the determination of the selection performed by the observer when detecting signals of a single frequency, the problem was to insert the probe signals of various frequencies with detectabilities equal to that of the center frequency, or the "signal to be detected," and to do so without altering the underlying selection process we wished to measure.

B. Description of the Method

The essential feature of the probe-signal method is simply to establish first a listening strategy in the observer and then, occasionally insert novel stimuli to determine that strategy. This method is not unique to the experiments reported here (e.g. Karoly and Isaacson, 1956), but we have developed the method and used it systematically. The observer is placed in a listening situation that nominally requires the detection of signals of a single frequency; these we will call the *primary signals*. On infrequent, randomly determined trials, a *probe signal* is presented in lieu of the primary signal. Probe signals are presented with various frequencies sampled from a band of frequencies centered on that of the primary signal, as represented in Fig. 1. The various probe signals and the primary signal, each of a different frequency, are all presented with equally effective energy, that is, with very nearly the same amplitude.[1] In this manner, equally detectable signals are sampled from a band of frequencies in a fashion similar to the engineer sampling from a uniform energy spectrum.

The initial instructions given the observers were written as though designed for an experiment to investigate the detection of signals of a single frequency presented against a continuous background of noise. The instructions included attempts to encourage the observers to believe that the frequency of the signals would be constant, but omitted any explicit statement to that effect. Several other aspects of the method were also intended to avoid any alteration of the underlying selection process by the insertion of the probe signals *per se*.

To avoid informing the observer, or making him "aware," that signals at frequencies other than that of

[1] The various probe signals and the primary signal, all of different frequencies, are presented with slightly different energies such that all signals would be expected to be equally detectable if each were the one signal to be detected in a typical, single-frequency signal-detection listening condition. For the frequency range of concern here, the difference in energy required to make all signals equally detectable is relatively small (Green, McKey, and Licklider, 1959). Therefore, to emphasize the fact that all the signals at the various frequencies would be expected to be equally detectable if presented alone in single-frequency experiments, we say that all signals were presented with equally effective energy.

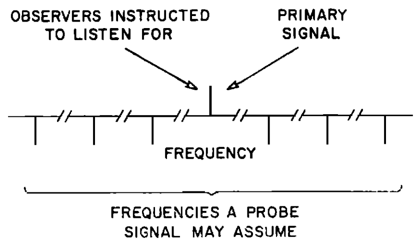

FIG. 1. A schematic representation of the probe-signal method. After the observer is trained to detect primary signals of a single frequency, probe signals at various other frequencies are presented infrequently, in lieu of the primary signal. Primary signals and all probe signals are presented with very similar amplitudes, which would be expected to render then all equally detectable if presented alone in single-frequency experiments. Estimates of the detectability of the signals of the various frequencies are obtained concurrently. The method provides data for a frequency-response characteristic of the observer nominally detecting the primary signals of a single frequency.

the primary signal were being presented, probe-signal trials were inserted infrequently and the occurrence of consecutive probe-signal trials was precluded. Observers were not informed regarding the correctness of their responses. To encourage the observer to expect only the primary-signal frequency, practice was provided with highly detectable signals in a single-frequency condition both during the initial familiarization sessions and during the initial portion of most other sessions.

Other techniques were used to remind the observers of the frequency of the primary signal. In Expt. 1, each trial block began with four special primary-signal trials for which the observers were told the location of the signal and during which the first two signals were presented with an unusually high intensity. In Expt. 4, the observer was presented a sample of the primary signal at the start of each trial.

We expected the aggregate of these procedures and instructions to provide concurrent detectability measures for the signals at the various frequencies. With those data, the frequency-response characteristic could be specified for the human observer detecting signals of a single frequency.

II. APPLICATIONS OF THE METHOD

A. General Procedure

Those aspects of procedure common to all experiments are presented in this Section. Other details are provided in the Sections describing the individual experiments.

A single experimental session was conducted on any one day. A session had between 10 and 13 blocks of trials and lasted 2 to $2\frac{1}{2}$ h. A block of 75 to 100 trials required 6 to 8 min. A pause of 2 to 3 min was provided between all blocks, except that once or twice a session, a pause was extended to approximately 10 min.

The trial structure was basically that of the common, two-alternative, temporal-forced-choice 2ATFC experiment in which the *a priori* presentation probability of the signal was 0.50 for each of the two observation intervals (e.g., Green and Swets, 1966). The instructions to the observer did not request identification of the signal, but only that he indicate by his response the presence of the signal during one of the observation intervals of each trial. Two types of trials, the primary-signal trial and the probe-signal trial, were defined by the experimenter but not for the observer. The two types of trials differed only in the specifications of the signals presented.

In blocks with both types of trials, the order of presentation of the two types of trial was determined by a table of random numbers (Rand Corporation, 1955). On any given trial, the type of trial presented was instrumentally independent of the observation interval in which the signal was presented and these two events were determined by separate, consecutive sampling from the same random-number source. The nominal (sampling) presentation probability was 0.70 for the primary-signal trial and 0.30 for the probe-signal trial; but a further constraint was imposed on the actual trial sequence such that two probe-signal trials could not occur consecutively in a block of trials. In each of the experiments, probe signals were observed to occur in 23% of the trials. During any one block of trials, all probe signals were of the same frequency.

For each observer, the earphones (Permoflux PDR-10) of a binaural headset were wired in parallel and in phase. The several headsets were wired in parallel. A noise generator (Grason–Stadler model 455-C) provided a continuous noise with a spectral level of approximately 65 dB SPL. The 0.25-sec signal was added to the noise by gating an oscillator output without regard to phase and without using special devices.

In an attempt to make the probe signals and the primary signal all of equal detectability, the amplitude of each probe signal was adjusted in proportion to the separation of its frequency from the frequency of the primary signal (Green, McKey, and Licklider, 1959). Specifically, probe signals with frequencies below that of the primary signal were presented with amplitudes lower than that of the primary signal by 0.2-dB-per-100-Hz separation from the frequency of the primary signal. The amplitude of each probe signal with a frequency higher than that of the primary signal was determined by the same relation and was greater than that of the primary signal.

Four experiments are reported. The principal differences in the procedures among the four are: the number of different probe-signal frequencies used; the frequency range covered by the probe signals; the distribution of the probe-signal frequencies over experimental sessions; and the number of experimental sessions devoted to obtaining data for the frequency-response characteristic.

B. Experiment 1

1. Introduction

This was the initial experiment using the probe-signal method, and we view it as a gross test of the method. The primary signal was of 1100 Hz. We assumed the observer's selection process, tuned to 1100 Hz, would attenuate inputs at 700 Hz and at 1500 Hz so severely that he would "not hear" probe signals at those frequencies. We presumed that signals "not heard" would not upset the selection process, but at some point along the frequency dimension where the probe signals were near the primary-signal frequency, they would be "heard" and possibly become the stimulus for a change in the selection process.

We supposed that we could at least obtain data indicating which frequencies were "not heard" by beginning with probe signals at frequencies remote from 1100 Hz and subsequently introducing probe signals at frequencies which were progressively closer to 1100 Hz. If, because of this progression, the shape of the frequency-response characteristic of the selection process were broadened drastically, the remote frequencies would become more detectable. By sampling the detection of outlying frequencies on either side of 1100 Hz throughout the experiment, we could observe such an indicative change.

2. Procedure

Three of the temporal intervals of each trial were defined for the observer by three separate indicator lamps. These displayed: the warning interval (0.75 sec) at the start of each trial; the first observation interval (0.35 sec) beginning at the end of the warning interval; and the second observation interval (0.35 sec) that began 0.45 sec after the end of the first observation interval. A response interval of 2.5 sec began at the end of the second observation interval and terminated with the beginning of the warning interval of the next trial. A signal occurred during the latter 0.25 sec of one of the observation intervals.

A session consisted of 10 blocks of 94 trials each. The first four trials of each block had primary signals presented during the first observation interval, and the observers were informed of that fact. The first two trials of each block had the primary signal presented with an amplitude 10 dB higher than that of the primary signals later during the block. Responses were not recorded for the first four trials of each block. Primary signals were presented with an amplitude producing $10 \log E/N_0 = 12$, except for the first two trials of each block.

Only primary signals were presented during the first block of each session. The remaining blocks of the session contained probe-signal trials as well as primary-signal trials. The probe signals during Blocks 2–4 of each session were either all of 500 Hz or all of 1700 Hz, the particular frequency value alternating over sessions.

For the probe signals during Blocks 5–10 of each session, six pairs of frequencies were made from 600, 700, 800, 900, 1000, 1050, 1150, 1200, 1300, 1400, 1500, and 1600 Hz such that each pair was symmetrical about 1100 Hz, the frequency of the primary signal. Each pair was assigned to the probe signals during Blocks 5–10 for four consecutive sessions. The sequence of pairs of probe-signal frequencies over sessions began with the widest pair, 600 and 1600 Hz, and proceeded over 24 sessions with progressively narrower pairs to 1050 and 1150 Hz, the narrowest pair, during the final four sessions. During Blocks 5–10 of each session, the frequency of the probe signals alternated block by block between the members of the pair for that session.

Special sessions, presenting different listening conditions, were inserted between Sessions 12 and 13 and after Session 24 of the main experiment. The nature of those sessions and the reason for their inclusion are discussed in the results section below. Four young women, all with clinically normal hearing, were tested simultaneously during the six familiarization sessions, the 24 sessions of the main experiment, and the six special sessions. These observers had no previous experience in auditory experiments.

3. Results and Discussion

Figure 2 shows the results for the four observers. The performance of Observer 315 was quite poor throughout the experiment, and we are unable to derive much from those data. The other three observers showed quite obvious differences in their detection as a function of the frequency of the signal. For the probe signals at 900 and at 1300 Hz, all three observers performed at or near the chance level of 50% correct. Their detection of frequencies between 900 and 1300 Hz increased as the frequency of the signal approached 1100 Hz, where they were correctly detecting approximately 80% of the signals. For the frequencies more remote than 900 or 1300 Hz, performance appears to be hovering near the chance level.

The curves are not unlike what we would expect from certain types of frequency-selective processes. One interpretation would be that, at those probe-signal frequencies producing chance levels of detection, the selection process attenuates the signal to such a degree that it is effectively excluded, that is, "not heard." On a trial presenting a signal at one of those frequencies, the observer is then given a choice between two observation intervals, one experimentally containing noise alone and other, because of the selection process, in effect containing noise alone. However, one aspect of the data forces us to be wary in making conclusions.

Inset into each panel of the Figure are the data points for performance on the 1100-Hz primary signal on each of the 24 sessions of the experiment which produced the data for the curves. At least for Observers 313 and 314, there is a gradual and systematic decline in performance

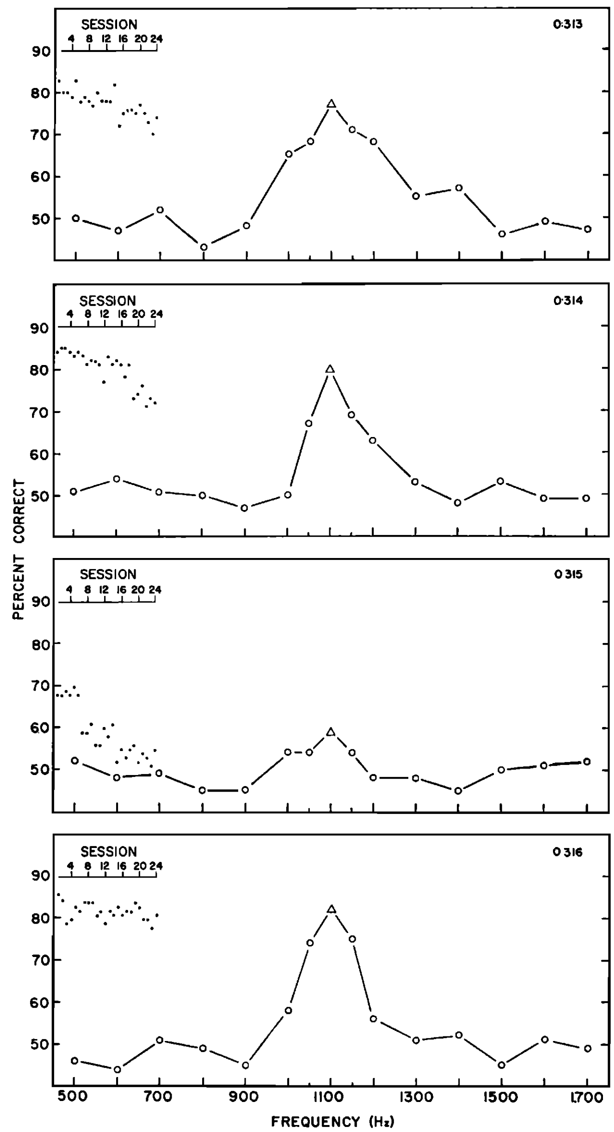

FIG. 2. The results of the probe-signal method in Expt. 1. Signals at the 15 different frequencies used were all presented with equally effective energy. The data points show the mean detectability of the signals at the various frequencies. The chance level of performance is 50% correct. Approximately 14 500 trials during 24 sessions provided the estimate for the 1100-Hz primary-signal detectability. For each of the probe signals at the 12 frequencies between 600 and 1600 Hz, the data points (circles) are derived from approximately 240 trials during four sessions. Approximately 730 probe-signal trials during 12 sessions provided the data for each of the points (circles) at 500 and 1700 Hz. The inset data points (solid dots) represent the detectability of the 1100-Hz primary signal during each of the 24 sessions of the experiment. Primary signals were presented with $10 \log E/N_0 = 12$.

on the primary signal over the 24 sessions. Recall that the progressive narrowing of the range of the pairs of frequencies for the probe signals was correlated with the progression of sessions of the experiment. Above, we expressed concern that as the frequency of the probe signals progressed toward that of the primary signal, a change in the underlying selection process could be induced. Such a change might be reflected in a decrement in performance on the primary signal, indicating that the observer was no longer behaving as he does in a single-frequency condition. We had obtained such a decrement.

We observed this gradual decline as the experiment progressed and therefore, between the prescheduled 12th and 13th sessions, with no change in instructions, we inserted two special sessions containing no probe signals. Performance on 1100 Hz during these special sessions was in line with the previously observed decline which continued over prescheduled Sessions 13–24, as shown by the inset data points. After the 24th prescheduled session, we conducted four additional special sessions containing no probe signals and again, the performance on the 1100-Hz signals continued its downward trend. The data for these special sessions are not presented here.

Beginning with the first session, part of each session had been devoted to probe signals at either 500 or 1700 Hz, the particular frequency alternating over sessions. If the underlying selection process had been broadened with the progression of the sessions, the performance at 500 Hz and/or at 1700 Hz might reflect that fact by showing a progressive improvement. The data for 500-Hz signals and those for the 1700-Hz signals show no trends for any of the observers.

The observers served for a total of 36 sessions. After the third session, they were never informed of any change in the listening conditions. It would not be surprising if the observers had experienced a gradual, declining interest in the detection of signals. This possibility, together with the performance during the special sessions, and the performance on the 500- and the 1700-Hz signals, led us to suspect that the gradual performance decline reflected their reaction to the sheer monotony of the task rather than to the presence of the probe signals. In any case, the data from the probe-signal method as used in this experiment were more vulnerable to alternative interpretations than is desirable.

C. Experiment 2

1. *Introduction*

If the gradual decline in performance observed in Expt. 1 was caused by the monotony of the task, some technique to combat monotony was required that would not itself occupy much experimental time. In Expt. 2, we introduced a "novelty" into the experimental task by periodically interjecting blocks of trials containing only primary signals at an atypically low intensity. The range of frequencies covered by the probe signals in this experiment was narrower than that in Expt. 1 and the primary signal was 1000 Hz. Otherwise, this experiment was similar to Expt. 1.

2. Procedure

The structure of a trial in this experiment was like that in Expt. 1, except that no warning interval was provided and the durations of certain intervals were lengthened, as follows. The second observation interval began 0.5 sec after the termination of the first, and the response interval of 4.0 sec was terminated at the beginning of the first observation interval of the next trial. The intervals and durations in this experiment differ from those of Expt. 1 only because of limitations of the available apparatus.

A session consisted of 11 blocks of 100 trials each. Two types of sessions were conducted and they differed only during the first few blocks. Both types began with one block of primary signals only. Type A sessions continued with 10 blocks of both primary signals and probe signals. During A sessions, all primary signals were presented with $10 \log E/N_0 = 12$. Type B sessions continued with only primary signals during Blocks 2 and 3. The primary signals during the first three blocks of B sessions were presented with $10 \log E/N_0 = 10$. The eight remaining blocks in a B session contained both probe signals and primary signals presented with $10 \log E/N_0 = 12$. The first session, of type A, was followed by a type B session and a sequence in which the two types of session were alternated between pairs of consecutive days.

For the probe signals, six pairs of frequencies were made from 700, 800, 900, 925, 950, 975, 1025, 1050, 1075, 1100, 1200, and 1300 Hz such that each pair was symmetrical about 1000 Hz, the primary-signal frequency. Each pair was assigned to the probe signals for four consecutive sessions. The sequence of pairs of probe-signal frequencies over the 24 sessions began with the widest pair, 700 and 1300 Hz, and proceeded over sessions with progressively narrower pairs to 975 and 1025 Hz, the narrowest pair, during the final four sessions. The portion of a session containing probe signals was divided into two equal groups of consecutive blocks. In each such group of blocks, the probe signals were all of the same frequency, one of the pair assigned to that session. The frequency assigned to each group of blocks was alternated over the four sessions for each pair.

Three young women and a young man, all with clinically normal hearing, served as simultaneous observers during three familiarization sessions and 24 sessions of the main experiment. The observers had no previous experience in auditory experiments.

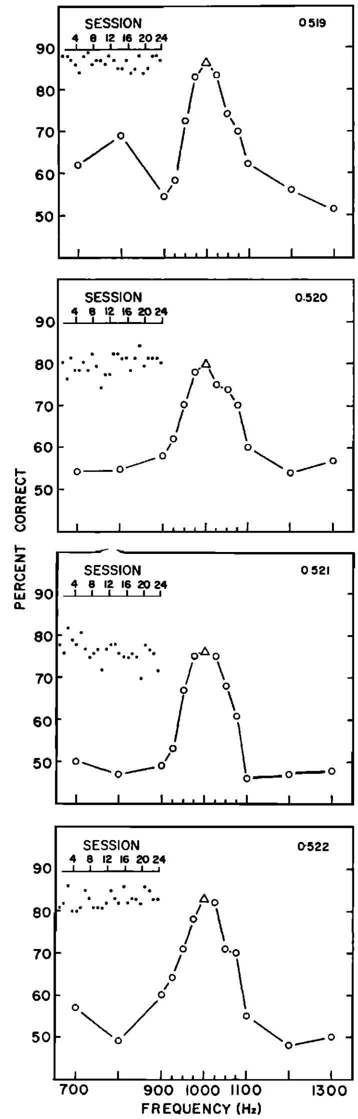

FIG. 3. Results from the probe-signal method in Expt. 2. Signals at the 13 different frequencies were all presented with equally effective energy. The data points show the mean detectability of the signals at the various frequencies. The chance level of performance is 50% correct. For the 1000-Hz primary signal, the data point is based on approximately 16 300 trials during 24 sessions. For each of the probe signals at the 12 other frequencies, the points (circles) are based on approximately 410 trials during four sessions. The inset data points (solid dots) represent the detectability of the 1000-Hz primary signal during each of the 24 sessions. Primary signals were presented with $10 \log E/N_0 = 12$.

3. Results and Discussion

Results for the four observers are shown in Fig. 3. The inset data points represent the performance on the 1000-Hz primary signal for each of the 24 data sessions. The general shape of the functions is very similar to that from Expt. 1. At frequencies ranging between 100 and 200 Hz on either side of the 1000-Hz primary signal, performance is at or near the chance level. Three of the four observers clearly were able to maintain their performance over the 24 sessions. Apparently, the minor change in the listening conditions in this experiemnt was insufficient to maintain stable performance for the other observer.

Table I compares the mean performance for each observer on the primary signals during Block 1 of the 12, alternate, A sessions with the mean primary-signal performance over all 216 blocks that contained both primary signals and probe signals during the 24 sessions. The data are for the primary signals presented with $10 \log E/N_0 = 12$. The tabular entries are based on approximately 1200 trials for the primary-signal-only condition and approximately 16 300 trials for the primary-signal-and-probe-signal condition. These data do not indicate that the presence of the probe signals had any sizable effect on the detectability of the primary-signal frequency.

D. Experiment 3

1. Introduction

In the two previous experiments, we had proceeded cautiously with the progression of the probe-signal frequencies over the experimental sessions. This caution was based upon our concern that probe signals at frequencies near the primary-signal frequency would be detected relatively well and could therefore become the stimulus for a change in the observer's selection process. This third experiment was conducted to determine whether such a precaution was in fact essential to the probe-signal method.

Experiment 3 was similar to Expt. 2 except that in this experiment, the sequence of pairs of probe-signal frequencies progressed from the widest to the narrowest back to the widest pair. If the presentation of probe signals with frequencies near the 1000-Hz primary signal disturbs the underlying selection process, that change should be reflected in the performance on the primary signal. Specifically, during the middle sessions of this experiment, when the probe-signal frequencies were near 1000 Hz, primary-signal performance should be lower than during other sessions of the experiment.

2. Procedure

Aside from the sequence of probe-signal frequencies over sessions and the signal levels, procedures in this experiment were the same as in Expt. 2. Primary signals were presented in this experiment with $10\log E/N_0 = 13$ for all blocks of type A sessions. The first three blocks of type B sessions contained primary signals with $10\log E/N_0 = 11$; and during the remaining eight blocks, the amplitude of the primary signal was higher with $10\log E/N_0 = 13$.

Two separated sets of two consecutive sessions were devoted to each pair of probe-signal frequencies. The sequence of probe-signal frequencies progressed from the widest pair, 700 and 1300 Hz, to 975 and 1025 Hz, the narrowest pair, during the first 12 sessions. The second half of the experiment used the reverse progression.

TABLE I. Mean percent correct for 1000-Hz primary signals during two conditions of Expt. 2, each with $10\log E/N_0 = 12$. Only primary signals were presented during the first trial block of each of 12 sessions evenly distributed over the 24 sessions of the experiment. Both primary signals and probe signals were presented during 216 other blocks of all 24 sessions.

Observer	Primary signals only	Primary signals and probe signals
519	87.3	86.4
520	79.7	79.7
521	77.3	76.4
522	81.3	82.8

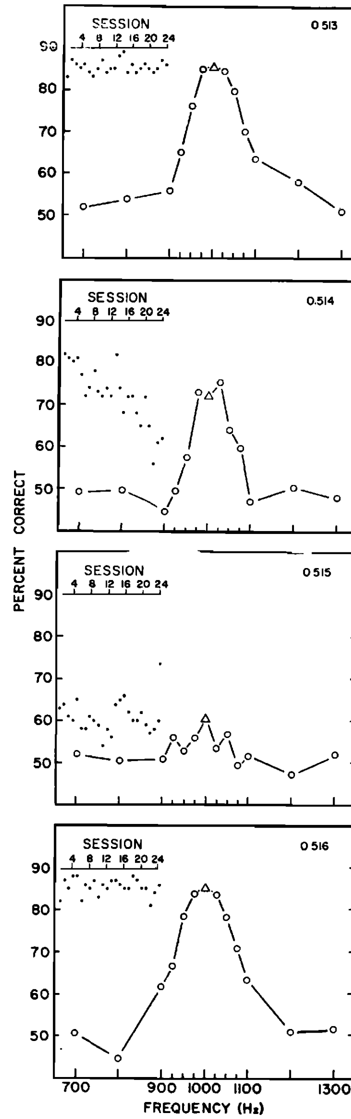

FIG. 4. Results from Expt. 3 with the probe-signal method. Signals at the 13 different frequencies were all presented with equally effective energy. The data points show the mean detectability of the signals at the various frequencies. The chance level of performance is 50% correct. The data point for the 1000-Hz primary signal is based on approximately 16 400 trials during 24 sessions. For each of the probe signals at the 12 other frequencies, the points (circles) are based on approximately 405 trials during four sessions. The inset data points (solid dots) represent the detectability of the 1000-Hz primary signal during each of the 24 sessions. Primary signals were presented with $10\log E/N_0 = 13$.

Three young women and a young man, all with clinically normal hearing, were tested simultaneously during three familiarization sessions and 24 experimental sessions. These observers had no previous experience in auditory experiments.

3. Results and Discussion

Figure 4 presents the results of this experiment. Observer 515 showed very little decline over the 24 sessions, as well as very little signal detection. The primary-signal performance of Observer 514 declined over the experiment, as shown by the inset data points. Three of the observors provided data for performance functions very similar to those of the two previous experi-

TABLE II. Mean percent correct for 1000-Hz primary signals during two conditions of Expt. 3, each with $10\log E/N_0=13$. Only primary signals were presented during the first trial block of each of 12 sessions evenly distributed over the 24 sessions of the experiment. Both primary signals and probe signals were presented during 216 other blocks of all 24 sessions.

Observer	Primary signals only	Primary signals and probe signals
513	85.5	85.5
514	79.7	72.5
515	71.0	60.5
516	86.8	85.5

ments. The performance estimate at 1000 Hz for Observer 514 appears to be somewhat depressed as compared to that to be expected from the rest of the curve, possibly because of the gradual decline over sessions. The inset data points for 1000-Hz performance during each session do not indicate that the progression of probe signals in this experiment altered the selection process, the data for Observer 514 notwithstanding.

Table II shows data from this experiment comparable to that in Table I from Expt. 2. The mean performance on the primary signals during Block 1 ($10\log E/N_0=13$) of 12 sessions distributed over the experiment is compared with the mean primary-signal performance during 216 blocks, from all 24 sessions, during which probe signals were presented as well as primary signals with $10\log E/N_0=13$. The tabular entries are based on approximately 1200 trials for the primary-signal-only condition, and on approximately 16 400 trials for the primary-signal-and-probe-signal condition. The tabular data for Observers 513 and 516 do not indicate that the presentation of probe signals had any significant effect on the detection of the primary signal. The data for Observers 514 and 515 indicate poorer performance on the primary signal when probe signals were also presented.

We can offer only a speculative explanation of these differences. Observer 515 admitted to no hearing loss or other basic auditory deficiency. She certainly was not an "average observer," and we can presume she was not highly motivated to perform well in the situation. Observer 514, who was a 13-yr-old girl, showed a decline over sessions which we had attributed to something like a lack of fascination with the task. It may be simply that during the first block of a session, these two observers were able to rise to the challenge of the task with greater gusto than during the later portions of the sessions.

E. Experiment 4

1. Introduction

In the previous three experiments, one of the major difficulties appeared to be the extensive experimental time required to obtain the necessary data. A shorter experiment was needed, one yielding at least a good approximation to the frequency-response characteristic of the observer.

2. Procedure

This experiment was made comparatively short by presenting a narrower range of frequencies for the probe signals, and by sampling the range more sparsely. Two other procedural changes were made in an attempt to get more reliable data. *First,* each probe-signal frequency was presented during each session. *Second,* to provide a stable referent for frequency-selective listening, a sample of the primary signal was presented at the beginning of each trial.

The structure of a trial in this experiment was similar to that of Expt. 1 with the warning interval and the two observation intervals defined for the observer by three separate indicator lamps. These three intervals were each 0.35 sec in duration. The first observation interval began 0.5 sec after the termination of the warning interval and the second observation interval began 0.35 sec after the end of the first observation interval. The response interval of 3.0 sec began at the end of the second observation interval and continued until the onset of the warning interval of the next trial. A signal occurred during the latter 0.25 sec of a 0.35-sec interval. Primary signals were of 1000 Hz.

A session consisted of 13 blocks of 75 trials each. Three conditions were presented. During the first two of these, Conditions A and B, a *sample signal* was presented on every trial during the warning interval and the observers were informed of that fact. Sample signals and primary signals were of the same duration, amplitude, and frequency. Primary signals were presented during all three conditions. The principle difference between the three conditons was as follows: Condition A presented sample signals but no probe signals; Condition B presented both sample signals and probe signals; Condition C presented probe signals but no sample signals. Regardless of the condition, each session began with a block of only primary signals presented with $10\log E/N_0=14$.

A. Condition A

The initial, single, familiarization session for the observers preceded the three consecutive sessions of Condition A. During Condition A, sample signals were presented on every trial but no probe signals were presented. Session 1 of this condition consisted of the following sequence of levels for the primary signal in terms of $10\log E/N_0$: 12 during Blocks 2–7; 11 during Blocks 8–13. These same primary-signal levels were used during Blocks 2–13 of Session 2 but the order of presentation was reversed. During Session 3, primary signals were presented with $10\log E/N_0=12$ throughout all blocks, 2–13.

B. Condition B

One session of "practice" intervened between Condition A and Condition B. Blocks 2–13 of each of the six, consecutive sessions of Condition B contained sample signals, probe signals, and primary signals presented with 10 $\log E/N_0 = 12$.

Only six frequencies were used for probe signals during this condition: 850, 925, 975, 1025, 1075, and 1150 Hz. Probe signals with each of these frequencies were presented during two blocks of each of the six sessions. The six probe-signal frequencies were assigned to blocks within a session such that each of the frequencies was used during one block of each of the halves of a session. The sequence of probe-signal frequencies over blocks within a session was different for each of the six sessions.

C. Condition C

The three, consecutive sessions of this condition began immediately following the last session of Condition B. These three sessions were identical with the first three sessions of Condition B, except that no sample signals were presented during Condition C.

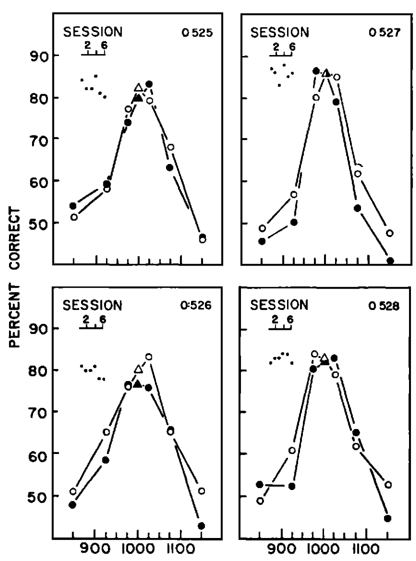

FIG. 5. Results from the probe-signal method for Conditions B and C of Expt. 4. Signals at the seven different frequencies were all presented with equally effective energy. The data points show the mean detectability of the signals at the various frequencies. The chance-level of performance is 50% correct. For Condition B (open symbols), the point at 1000 Hz is based on approximately 4000 primary-signal trials during six sessions. The six points for the probe-signal frequencies during Condition B (open circles) are each based on approximately 210 trials during six sessions. For Condition C (filled symbols), the point at 1000 Hz is based on approximately 2000 primary-signal trials during three sessions. The six points for the probe-signal frequencies (filled circles) are each based on approximately 100 trials during three sessions. The inset data points (solid dots) represent performance on the 1000-Hz primary signal during each of the six sessions of Condition B. Primary signals were presented with 10 $\log E/N_0 = 12$.

TABLE III. Mean percent correct for 1000-Hz primary signals presented with 10 $\log E/N_0 = 12$, during the three conditions of Expt. 4. Sample signals were presented during Conditions A and B only. Probe signals were presented during Conditions B and C only.

	Condition		
Observer	A	B	C
525	81.2	82.2	79.4
526	76.3	79.6	76.4
527	84.2	86.0	85.9
528	84.7	83.1	82.0

Three young women and one young man, all with clinically normal hearing, served as simultaneous observers for 14 sessions. These observers had no previous experience in auditory experiments.

3. Results and Discussion

Figure 5 displays the results of Conditions B and C of this experiment. The curves for Condition B (open symbols) indicate that with the probe-signal method, six sessions of the type used can be sufficient to obtain a good approximation of the frequency-response characteristic of the observer. Similar to the results of the previous experiments, performance declined to or near the chance level at approximately 150 Hz on either side of the 1000-Hz primary-signal frequency. The inset data points show the estimates of performance on the primary signal for each of the six sessions of Condition B. Of course, there was little opportunity for the data to demonstrate an orderly decline over the sessions. The results from Condition C (filled symbols) allow two conclusions. *First*, even in three sessions and in the absence of the sample signal, the probe-signal method may provide a good approximation to the frequency-response characteristic of the observer. *Second*, the only obvious effect produced by the removal of the sample signal was a slight decrement in the performance on the primary signal for some of the observers. This decrement in performance is also shown by the results presented in Table III.

Table III displays, for each observer, the mean percent-correct for the 1000-Hz primary signal presented with 10 $\log E/N_0 = 12$, for each of the three experimental conditions. The approximate number of trials determining the tabular entries for Conditions A, B, and C are 1725, 4000, and 2000, respectively, for each observer. The total change in the primary-signal performance over the three conditions was approximately 2% to 3% for any one observer. Comparison of performance during Conditions A and B indicates little change in the detection of the primary signal when probe signals were introduced during Condition B and that change was in the unexpected direction for three of the four observers.

III. SUMMARY AND CONCLUSIONS

Sixteen observers served in four experiments using the probe-signal method. Two of these observers showed very poor detection over all. The results for each of the other 14 observers demonstrated differential responding as a function of the signal frequency. The frequency-response characteristics for these 14 show correct detection of the center-frequency signal (1000 or 1100 Hz) between 75% and 90% of the time. The same curves show approximately 50% correct, or chance, detection of signals with frequencies at approximately 150 at 200 Hz on either side of the center frequency. There can be no doubt that observers nominally detecting signals of a single frequency presented against a background of continuous wide-band noise do select from the input and respond differentially to the frequency of the input signal.

There is a striking similarity between the obtained curves and frequency-response characteristics for filter devices. The results could be used to support a filter model of the behavior of the observer detecting signals of a single frequency. In the context of such a sensory filter model, the chance level of detection of the outlying frequencies would indicate that signals at these frequencies are attenuated to such an extent that they are, in effect, not heard. Whether the outlying frequencies are in fact not heard, or are heard but not considered signals, is a question for further investigation. Post-experimental inquiry did not reveal any evidence that the observers were "aware" of probe signals, and when informed of them, the observers reacted uniformly with surprise.

The shapes of the 14 obtained curves invite a comparison with the empirical data on auditory critical bands. For example, we could consider the obtained curves as filter characteristics and calculate the bandwidth at the half-power points. We assume a one-to-one relation between the detectability index d' and the signal power (Green, Birdsall, and Tanner, 1957). The primary-signal data converted to d' allows the determination of a percent-correct value corresponding to one-half of that d', a dervied performance level analogous to the half-power level of a filter. With that value of percent-correct, an estimate of the half-detectability, or half-power, bandwidth can be obtained from the graphical plot of the percent-correct data. In this manner, we obtained bandwidths of 120, 135, and 145 Hz for observers of Expt. 2, and of 105, 130, 125, and 140 Hz for observers of Expt. 4. (For other observers, the estimates of primary-signal detectability were questionable because of a decline in performance or they were obtained for a higher signal level.) These bandwidths are well within the range of some recent estimates of the critical band about 1000 Hz (Scharf, 1961).

The estimate of the bandwidth was fairly crude because of the number and location of the data points determining a curve. Nevertheless, the above bandwidths, in order, were obtained from curves with performance levels on the primary signal of 86%, 83%, 80%, 86%, 83%, 82%, and 80% correct, respectively. These data give a rough, inverse relation between the bandwidth and the performance level at 1000 Hz.

We have pointed out the possible relevance of these results to a filter model and the similarity of certain estimates derived from these results to critical-band estimates. However, we believe that the use of the data reported here either for support of a sensory filter model or as another estimate of a critical band should be deferred until there is a better understanding of the relation between the processes being measured by the probe-signal method, by various experiments on the critical band, and by other signal-detection experiments. Additional experiments are planned to inquire further into the nature of the selection process displayed by the probe-signal method.

The apparent success of the probe-signal method is encouraging. The fourth reported experiment demonstrated that frequency-response characteristics can be obtained with relative ease. Two conditions of that experiment, requiring only six and three sessions, respectively, produced frequency-response characteristics quite like those from the other three experiments, each employing 24 sessions. Evidently, we need not have been concerned, before conducting the experiments, that the probe signals would disturb the selection process being measured: At least, no such effect is obvious in the data. If this interpretation is correct, the probe-signal method may be a highly useful way to explore frequency selectivity in different listening situations.

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