THE EVALUATION AND CONTROL OF ACOUSTICAL STANDING WAVES¹

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Calibration of a standard pigeon box subsequently modified for use as an acoustical chamber in a frequency discrimination experiment revealed that the enclosure was not acoustically "flat". Standing waves were detected at each of the six frequencies measured. To ascertain whether the maximum standing waves recorded (3.0 dB) could serve as an added or alternative cue for pigeons tested in the chamber on a frequency discrimination problem, pure-tone intensity difference thresholds were determined for two pigeons at 1.0, 2.0, and 3.0 KHz. The results of the experiment indicated that the smallest intensity difference detectable was 10.0 dB, a value that was 7.0 dB above the maximum standing wave measured in the box. These data suggest that the modified pigeon chamber is suitable to test pure-tone frequency discriminations in pigeons in the range of 1.0 to 3.0 KHz.

Measurement and control of stimuli used in animal psychophysical studies are essential to minimize the likelihood that the subjects studied can make discriminations by using non-relevant stimulus parameters. One such possible extraneous cue present in auditory experiments is that caused by the presence of standing waves. This study was designed to evaluate and control the presence of standing waves in a Lehigh Valley pigeon box employed as an acoustical testing environment to measure frequency difference thresholds in pigeons.

CALIBRATION OF THE ACOUSTICAL CHAMBER

Unless one uses an anechoic chamber or perfectly reverberating room to conduct a free-field frequency discrimination experiment,

standing waves are likely to be present. A standing wave is defined in the McGraw Hill Encyclopedia of Science (1960) as one "which is formed when the boundary conditions on traveling waves are such that the transmitted and reflected waves add up so that amplitudes are constant at a fixed position in space but vary from point to point. The points in space where the amplitudes are zero are called nodes. Antinodes are points where amplitude is maximum." The occurrence of standing waves in the acoustical environment is important in frequency discrimination studies because the subject may, by moving its head appropriately in the sound field, detect intensity differences between stimuli and use them as additional or alternative cues in making discriminations. The occurrence, locus, and magnitude of standing waves in the testing chamber depends in part on the dimensions and geometrical configuration of the space, the stimulus wavelength, and the absorption coefficient of the inner walls surrounding the chamber. The higher the amplitude of the standing wave, the more likely it is to become a discriminable stimulus. For example, in a given chamber, a 1-KHz pure tone may generate a sizeable standing wave, whereas a 3-KHz tone may not. Even though the intensities of the two frequencies had been equated for loudness according to the subject's sensitivity function, the presence of a high amplitude standing wave associated with one stimulus could result in an intensity mismatch in certain test-

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chamber locations. Standing waves should therefore be curtailed as much as possible to minimize their potential stimulus value.

Apparatus

A Lehigh Valley (Model 1519) pigeon test chamber was used as the acoustical enclosure. Measurements were made under three conditions: (A) the standard chamber including the 5.1-cm speaker provided by the manufacturer; (B) the standard chamber with a 10.2-cm KLH model 12 speaker, mounted on the wall opposite the response keys; this speaker, encased in a particle-board sound baffle and fastened at a 45-degree angle at the junction of the rear wall and ceiling, was chosen because its frequency response was "flat" between 1 KHz and 3 KHz; the 45-degree mounting angle was chosen to help minimize reflections that could form standing waves; (C) the chamber described above, modified in accordance with the recommendation of the engineering staff of the Sound Section of the National Bureau of Standards to line floor, walls, ceiling, and door with Corning fiberglass (PF-703) to shield out external noise and reduce standing waves within the chamber. The standard pigeon chamber measured 35.4 by 36.4 by 31.0 cm. These dimensions were reduced to 22 by 27 by 29 cm when the fiberglass lining was installed.

Two response keys were centered on the intelligence panel and mounted 0.5 cm apart at a distance of 23.5 cm from the floor (21.5 cm from the floor in the unmodified chamber). An opening that provided access to the food magazine was located 6.0 cm below the response keys. All intensity measurements were made using a General Radio sound-level meter (1551 C). The meter was calibrated by General Radio Corporation, using their standard calibration equipment. The calibrations were periodically rechecked by the manufacturer. The meter was recalibrated at the National Bureau of Standards Sound Section. These calibrations were within 1 dB of the manufacturer's calibrations.

Initially, the microphone that had come with the meter, mounted on a wooden block, was used to make the intensity readings within the experimental chamber. This calibration system proved to be inadequate because the wooden block, microphone, and cable coupling were highly reflective surfaces and were the

source of large standing waves. To minimize these artifacts, and approximate as closely as possible the sound intensity at the pigeon's ear, another mounting configuration was developed. A taxidermally stuffed pigeon with two Shure microphones (model MC 30 J) binaurally mounted on its head and centered respectively over its right and left meatus was used in place of the General Radio microphone and wooden block. The Shure microphones were calibrated by the manufacturer. The frequency response curves provided with the microphones indicated that their frequency response differed from one another by less than 1 dB in the range of 1 KHz to 3 KHz. Each microphone was also calibrated by the National Bureau of Standards. The microphones were calibrated in an anechoic chamber relative to each other and the General Radio microphone using a General Radio automatic frequency response analyzer. During the course of the experiments, the output of each Shure microphone was monitored separately. Sound-level readings were made with each microphone at all of the measurement loci described below. The output for each microphone was led back to the sound-level meter via shielded, impedance-matched cable. This measurement system had the advantage that the absorption characteristics of the feathers could be taken into account and the microphones would more accurately approximate stimulus intensity at the pigeon's ear. The pure-tone stimuli used to measure the standing waves in the chamber were generated by a set of six battery powered, programmable Twin T oscillators (Maynard, 1964) built by the Biomedical Electronics Section of the Neuropsychiatry Division of Walter Reed Army Institute of Research. An analysis of the harmonic distortion of the six stimulus frequencies used revealed that the oscillators had less than 0.1% distortion (measurements were made using a Heathkit model IM-12 harmonic distortion meter).

The frequency response of the KLH speaker was calibrated at the Sound Section of the National Bureau of Standards. The stuffed pigeon was placed in the chamber with its beak touching a point on the front wall halfway between the centers of the response keys. This locus was termed the "standard position". The chamber, insulated as described above and with its door closed, was placed in an anechoic

chamber. The frequency response of the speaker was measured automatically using a General Radio automatic frequency response recorder. The results of the calibration revealed that the speaker's frequency response was essentially flat between 1 and 3 KHz, except for a narrow 4.0-dB V-shaped notch at 2.0 KHz. This was found to be due to sound reflections from the response keys and was compensated for by increasing the sound level by 4.0 dB when setting the intensity of the 2-KHz oscillator.

Procedure

The basic procedure for measuring standing waves was the same for each of the three chamber configurations. The stuffed pigeon was placed in the standard position and measurements of sound levels were made at 3.0, 2.0, 1.5, 1.25, 1.05, and 1.0 KHz. All frequencies were initially set at 70 dB re $20\mu\text{N}/\text{m}^2$ ($0.0002\text{ dynes}/\text{cm}^2$). We did not determine equal loudness functions for pigeons but we assumed that the function would be flat between 1 and 3 KHz at this intensity based on the observations of Trainer (1946) and Heise (1958). The A scale of the sound-level meter was used because the weighting network at this setting most closely approximated the free field sensitivity function for pigeons. (Trainer, 1946; Heise, 1953). Measurements were made at 1-cm intervals to the right and left of the standard position for a total of 4 cm in both directions. The same procedure was repeated at distances

of 1, 2, 4, and in the case of the unaltered chamber, 8 cm behind the standard position. Thus, readings for each frequency were made at 36 locations within the chamber for both of the altered configurations (B and C) and 45 measurements per frequency were made in the unaltered chamber (A).

RESULTS AND DISCUSSION

Standing waves were assumed to be present if intensity differences were detected between frequencies at any given locus in the test chamber. For example, if 1 KHz and 3 KHz, which had been adjusted to have the same intensity in the standard position, differed in intensity at any other locus within the chamber, standing waves were demonstrated.

The data collected during the course of the calibration study are shown tabulated in Table 1. A total of 1566 measurements were made ($261/\text{chamber} \times \text{three chamber configurations} \times \text{two microphones}$). Each number in the table represents the maximum standing wave recorded with either microphone for the frequencies measured. For example, the maximum standing wave recorded in the standard box configuration (row A of Table 1) was 19.5 dB at 1.05 KHz.

In general, the data confirmed that none of the three chamber configurations was acoustically "flat". Standing waves were recorded at each of the frequencies measured in each chamber configuration. The largest standing waves were recorded at 3.0 and 1.05 KHz in

Table 1

Maximum standing wave in dB above the sound level of the 1-KHz stimulus at the same location in the test chamber for three chamber configurations (see text for details).

<i>Perpendicular Distance From Key (cm)</i>		<i>3 KHz</i>	<i>2 KHz</i>	<i>1.5 KHz</i>	<i>1.25 KHz</i>	<i>1.05 KHz</i>
A	0	18.5	3.0	8.0	6.5	19.5
	1	17.5	5.5	16.0	3.5	15.5
	2	13.5	5.5	15.0	4.0	15.0
	4	12.5	6.0	16.0	6.0	15.5
	8	11.5	9.5	17.5	9.0	17.5
B	0	6.5	5.0	7.0	4.5	2.5
	1	5.0	7.5	7.0	7.5	3.0
	2	2.0	9.5	8.0	7.0	3.5
	4	4.0	12.0	11.5	8.0	4.5
C	0	2.5	2.0	1.0	0.5	1.5
	1	3.0	2.0	0.5	0.5	1.0
	2	2.5	3.0	1.5	1.5	1.5
	4	3.0	3.0	1.0	1.0	1.0

the standard chamber. Change in the size, quality, position, and angle of the speaker (row B of Table 1) sharply reduced the intensity of the recorded standing waves at all frequencies (note particularly the changes at 3.0 and 1.05 KHz). The final chamber configuration (row C of Table 1) proved to be the best acoustical environment of the three tested. Maximum standing waves of 3.0 dB were recorded at 3.0 and 2.0 KHz. As the data in row C indicate, maximum standing waves in the insulated chamber ranged from 3.0 to 0.5 dB. These data represent a marked improvement over those recorded in the other two chamber configurations. Further, the data shown in row C reveal that as the frequency difference between the standard stimulus (1 KHz) and the variable stimuli decreased, the magnitude of the recorded standing waves decreased to an average of 1.0 dB, an intensity level within the error of measurement of the sound-level meter. In addition, the data indicate that the standing waves were least prominent in the vicinity of the response keys.

In summary, the data support the conclusion that large standing waves were present in the standard pigeon chamber and that the alterations in the test chamber's configuration materially reduced the amplitude of the standing waves. Given that measurable standing waves were detected at all frequencies in chamber configuration C, a question that remained was whether the standing waves were still of sufficient magnitude to serve as discriminable extraneous cues. In order to answer this question, we performed an experiment to determine whether pigeons could distinguish between pure-tone intensity differences as small as 3.0 dB. If the pigeons could not reliably detect pure-tone intensity differences of 3.0 dB, then the insulated test chamber would be regarded as satisfactory for testing pure-tone frequency discriminations.

PURE-TONE INTENSITY DIFFERENCE THRESHOLDS

Subjects and Apparatus

Two male White Carneaux pigeons (*Columba livia*) 6 and 7 yr old respectively, were obtained from the Palmetto Pigeon Plant, Sumter, South Carolina. The pigeons were housed in individual cages and had free access to food for three weeks after they arrived in

the laboratory. At the end of this time they were weighed and the recorded weight was considered their 100% weight.

The experimental chamber was the same as that described above. The stimulus source was a Hewlett Packard sine wave generator (model 200 CD). The attenuator used to regulate the intensity of the stimuli (1 KHz, 2 KHz, and 3 KHz) was a Hewlett Packard decade attenuator (model 350A). A Grason-Stadler recording attenuator (model 3262A) arranged the intensity of the variable stimuli. At each frequency, the standard stimulus was set at 65 dB and the variable stimuli were: 90, 80, 75, 70, and 65 dB respectively. A Grason-Stadler noise generator (model 901B) with built-in mixer was used to provide a 50-dB background noise in the chamber. The experiment was arranged and recorded automatically using electro-mechanical relays, clocks, counters, and cumulative recorders, which were located in an acoustically isolated room adjacent to the experimental room.

Calibration Procedure

At the start of each experimental session, the ambient noise in the chamber was calibrated using the stuffed pigeon in the standard position. Next, the background noise level in the chamber was set at 50 dB by adjusting the noise gain control on the noise generator. After this had been completed, the intensities of the standard and variable stimuli were set.

General Experimental Procedure

After key-peck training, the discrimination training phase of the experiment was initiated. During discrimination training, the pigeons were trained to peck at the left key (transilluminated with red light) 30 times in the presence of the variable stimulus (90 dB at 1 KHz) and to peck 30 times at the right key (transilluminated with green light) in the presence of the standard stimulus (65 dB at 1 KHz).

An initiating response was scheduled to ensure that the pigeon's head would be in approximately the same locus at the start of each trial. Both response keys were transilluminated with white light at the beginning of each trial. A single peck on either key (the initiating response) turned on the stimulus scheduled for that trial, terminated the white light, and turned on the red and green stimuli

behind the left and right response keys respectively.

After 30 pecks on the key appropriate to the stimulus being presented, the pigeon received 1.5-sec access to the feeder. A trial was recorded as incorrect if a bird pecked 10 times on the key inappropriate to the stimulus being presented. Incorrect responses resulted in a 5-sec timeout, during which the house and keylights were darkened and key pecks were ineffective. A correction procedure was used so that after an incorrect response, the stimulus scheduled for a particular trial continued to be presented until the bird responded 30 times on the key appropriate to the stimulus. When the correct response was finally made, the bird received 1.5 sec of the magazine light only. Then, the program advanced the experiment to the next trial. Training sessions consisted of 240 trials, 120 presentations of the standard stimulus of 65 dB and 120 trials of the variable stimulus, 90 dB, presented in quasi-random order. The pigeons continued to receive training until they reached a criterion of 90% correct or better on three consecutive sessions. Once this criterion was achieved, difference threshold testing was begun.

Each session during the threshold testing phase consisted of a total of 240 trials. The test stimuli were presented in blocks of 20 trials each. A block consisted of 10 presentations of the standard and 10 presentations of the variable stimulus. Thus, one value of the variable stimulus was presented in each block in a quasi-random order with the standard stimulus. The intensity of the variable stimulus was systematically lowered until in the last block the pigeon had to discriminate between 65 dB (standard) and 68 dB (variable) at 1 KHz.

The first 20 trials in each session were termed "warm-up" trials. These data were discarded. The next 20 trials were termed "assessment" trials. The stimuli scheduled in this block were 90 dB and 65 dB. If a pigeon responded correctly on 18 of 20 trials (90%), the program advanced the experiment to the next problem (standard 65 dB, variable 80 dB). If, however, it achieved less than 90% correct during assessment, it received the training problem (65 dB *versus* 90 dB) for the remainder of the session.

If the pigeon achieved the assessment requirement, the program advanced the experi-

ment and allowed the pigeon to receive all of the test problems. When the last discrimination was completed, the experiment was run through a second time starting with the first problem. The first 20 trials of the second run were regarded as "warm-up" trials and the data were discarded. However, in this second run, no assessment was used. Irrespective of the pigeon's per cent correct on the first problem, the program advanced the experiment to the second problem. The session terminated after 240 trials were completed.

The difference threshold was calculated as follows: per cent correct was plotted as a function of pure-tone intensity. The point at which the resulting psychometric function first crossed the 75% correct line was taken as the point of subjective equality (PSE). The difference threshold was obtained by subtracting the intensity of the variable at the PSE from the intensity of the standard. Sessions in which the psychometric function crossed the 75% line twice were discarded. The behavioral procedure and method of threshold calculations are described in greater detail in Krasnegor (1971) and Hodos and Bonbright (1972).

The pigeons were both initially tested at 1 KHz. Testing was continued until the birds met the following criterion: five successive testing sessions during which no difference threshold exceeded $\pm 25\%$ of the mean difference threshold during those five sessions.

During the next phase of the experiment, the pigeons were tested on alternate days at different frequencies. Pigeon C-504 was tested at 1 KHz and 3 KHz, while C-505 was tested alternately at 1 KHz and 2 KHz. Once thresholds had been determined under these conditions, the final phase of the experiment was begun. Thresholds for intensity differences were obtained at 3 KHz for Pigeon C-505 and at 2 KHz for Pigeon C-504.

RESULTS AND DISCUSSION

The results of the pure-tone intensity study are plotted in Figure 1. The daily thresholds obtained with 1-KHz tones are plotted in panel A. Pigeon C-504 required eight sessions to stabilize and had a mean threshold of 16.6 dB, while C-505 required only five sessions to stabilize and had a mean threshold of 15.1 dB.

The data obtained in phases 2 and 3 are plotted respectively in panels B, C, and D. Note that the data are grouped by frequency,

Fig. 1. Difference thresholds for Pigeons C-505 and C-504. The means appearing in each panel represent the average difference threshold obtained for each of the birds based on the data points appearing in the figure.

rather than the sequence in which the data were collected. The results plotted in panel B indicate that C-504 maintained the same difference threshold at 1 KHz, while C-505 showed a change in mean threshold difference to 13.6 dB, a decrease of 1.5 dB. The data plotted in panels C and D represent the difference thresholds for the two pigeons at 2 KHz and 3 KHz respectively. Both pigeons required the same number of sessions to reach stability. Pigeon C-504 showed a higher difference threshold at each frequency in comparison to C-505. For individual birds, however, the thresholds were quite similar across frequencies. The numbers appearing as inserts at the bottom of panels B,

C, and D represent the mean difference threshold for each pigeon. The data indicate that neither bird was able to detect stimulus differences as small as 3.0 dB. Moreover, the pure-tone intensity difference thresholds are considerably higher than the 4- to 7-dB white-noise intensity difference thresholds reported by Krasnegor (1971) using the same procedure and chamber configuration C.

The threshold experiment demonstrates that the maximum intensity difference due to standing waves (3.0 dB) would probably not be a discriminable cue in a pure-tone frequency discrimination experiment. The smallest intensity difference that either of the pigeons

could detect on 75% of the trials was 10.0 dB (C-505 at 2 KHz). This value is 7.0 dB higher than the maximum standing wave measured in study 1. In addition, the data from the 3.0-dB discrimination problem (65 versus 68 dB) at each of the frequencies was subjected to a signal detection analysis (Pollack and Norman, 1964). The data points were found to lie on or quite near the negative diagonal of the unit square, which further suggests that the 3.0-dB intensity difference was not detectable. In conclusion, the physical measurement of pure-tone intensity and the behavioral observations indicate that the chamber described above (chamber C) is satisfactory for the study of pure-tone discriminations in pigeons in the range of 1 to 3 KHz.

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