NOTS TP 4178

AUDITORY THRESHOLDS OF THE BOTTLENOSED PORPOISE

(*Tursiops truncatus*, Montagu)

by

C. Scott Johnson

Research Department

ABSTRACT. Standard operant conditioning techniques were used to train a bottlenosed porpoise to respond to pure tone signals by pushing a lever-operated switch. An audiogram was obtained over the frequency range from 75 hertz to 150 kHz. The lowest thresholds (greatest hearing sensitivity) occurred in the frequencies near 50 kHz at a level of about -55 decibels (re 1 microbar). The effective upper limit of hearing for the experimental animal was determined to be 150 kHz. There was no indication of sensitivity to near-field displacements such as those observed in fish.

U.S. NAVAL ORDNANCE TEST STATION
China Lake, California
November 1966

U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

J. I. HARDY, CAPT., USN
Commander

WM. B. MCLEAN, PH.D.
Technical Director

FOREWORD

This study is one in a series of studies being conducted on porpoises. The work was supported by Foundational Research funds, Bureau of Naval Weapons Task Assignment R360-FR 106/216-1/R011-01-01.

This report is transmitted for information only. It does not represent the official views or final judgment of this Station.

Released by
HUGH W. HUNTER, Head
Research Department
19 August 1966

Under authority of
WM. B. McLEAN
Technical Director

NOTS Technical Publication 4178

Published by..Research Department
Collation...............Cover, 15 leaves, DD Form 1473, abstract cards
First printing....................................150 unnumbered copies
Security classification.................................... UNCLASSIFIED

CONTENTS

Appendixes:

BLANK PAGE

ACKNOWLEDGMENT

The author acknowledges the help of the late Dr. Keller Breland of Animal Behavior Enterprises who made several helpful suggestions concerning the experimental procedure used and the help and advice of R. E. Bailey, formerly with this Station and now with Animal Behavior Enterprises, during the training of the porpoise.

INTRODUCTION

The hearing ability of cetaceans has been speculated about for many hundreds of years (Ref. 1 and 2), and although their hearing acuity has been generally accepted as being very keen, little quantitative information on their hearing capabilities has been reported in the open literature. Kellogg and Kohler (Ref. 3), Kellogg (Ref. 4), and Schevill and Lawrence (Ref. 5 and 6) have studied the upper frequency hearing capabilities of the bottlenosed porpoise or dolphin (Tursiops truncatus, Montagu).

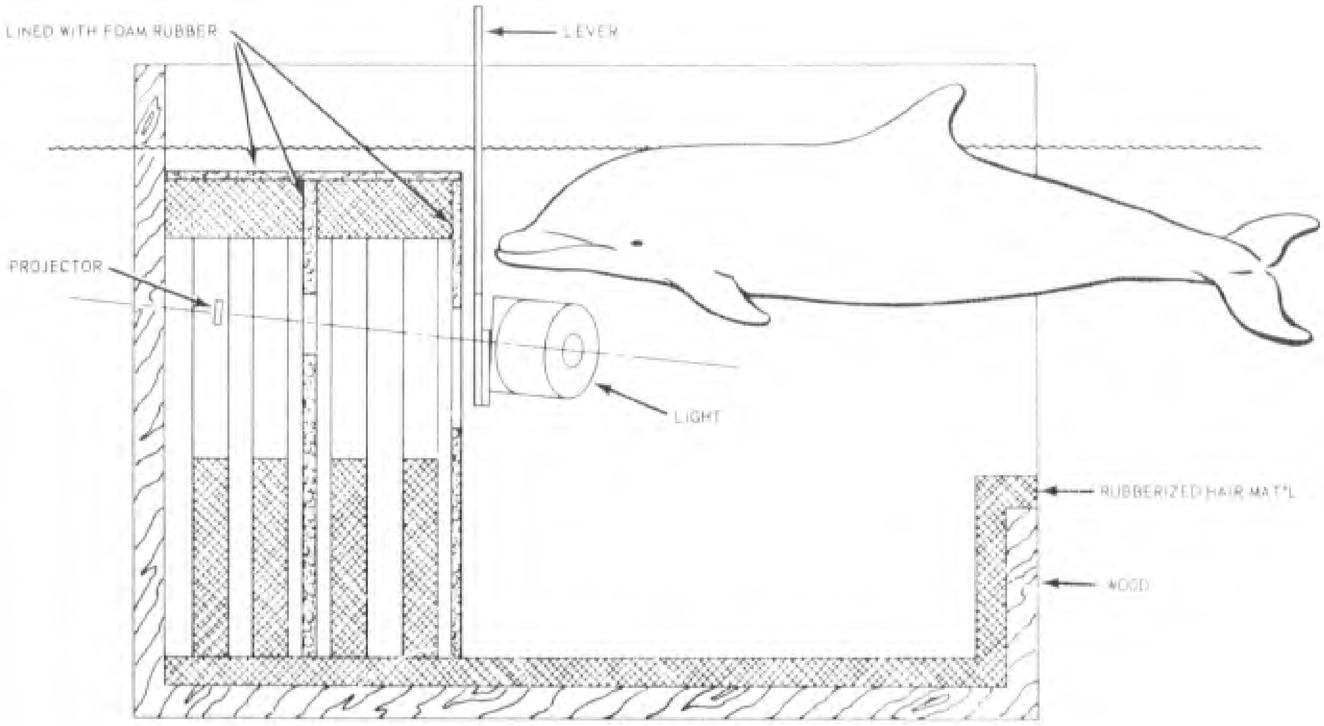
The bottlenosed porpoise is known to possess a highly developed echolocation system (Ref. 7, this paper gives references to earlier work) with which they can navigate and find food in water so turbid that vision is impossible. In order to understand their echolocation system more completely, a series of tests of the porpoises' hearing capabilities has been undertaken.

The purpose of the tests described herein was to determine the absolute pure tone sound detection thresholds of Tursiops truncatus over the major portion of their range of hearing.

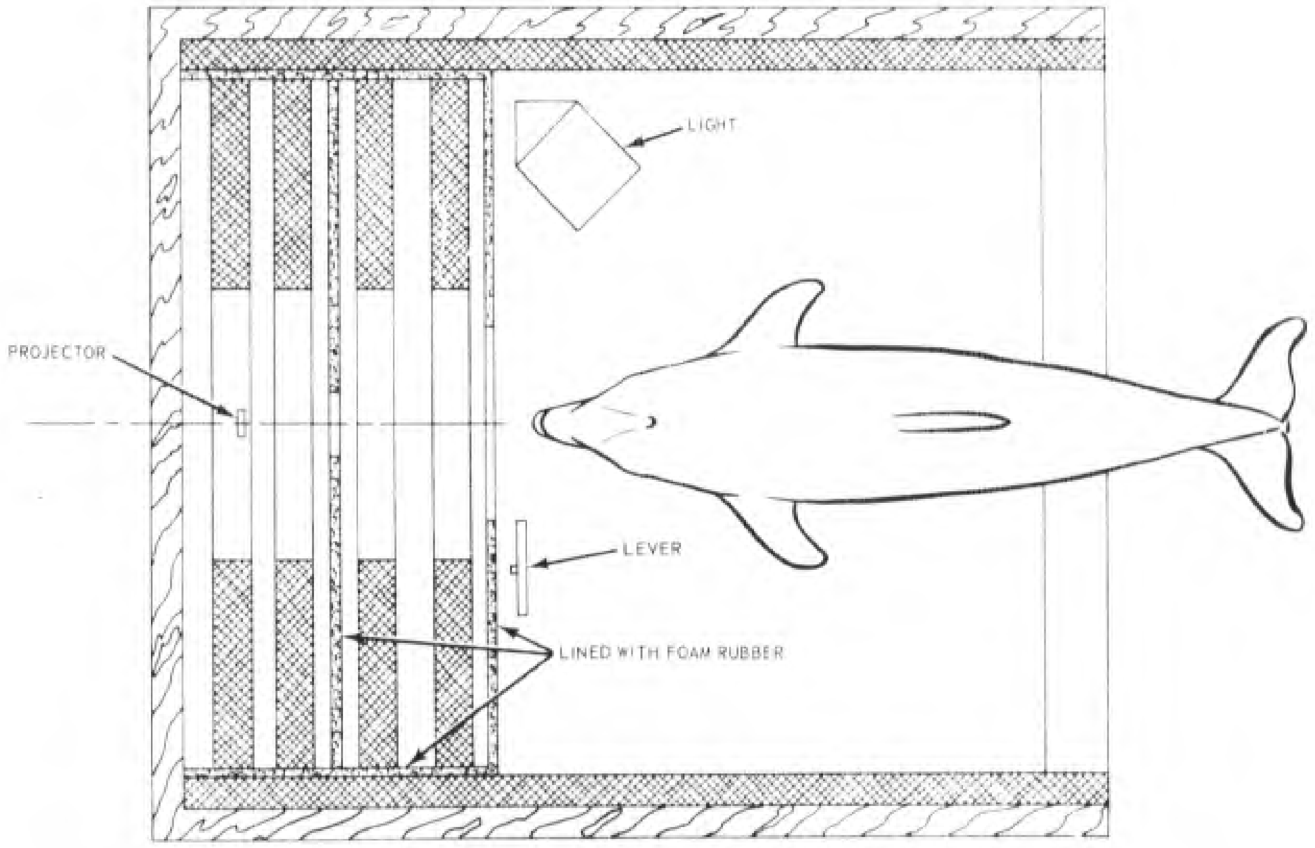
TEST DESCRIPTION

TEST SITE

The tests were performed at the Marine Biology Facility, Point Mugu, California. Preliminary training and a feeding rate study (see Appendix A) were conducted in a canvas and aluminum tank 7.6 meters in diameter and with a water depth of 0.9 meters. All of the data were taken using a redwood tank 8.2 meters in diameter having a water depth of 1.3 meters. The side and bottom of the tank were of 5-cm redwood. On one side of the tank a stall-like enclosure was constructed of 5-cm redwood. It had two sides, a bottom, and was closed at one end. The closed end was fastened to the side of the tank with the open end toward the center of the tank. The stall was lined with 5 cm of rubberized pig-hair and horsehair packing material (see Fig. 1). A sound source was positioned near the closed end of the stall and a system of sound reflecting and absorbing baffles was provided to direct the sonic energy into the stall. In this way a region of relatively high sound intensity was produced in the stall. The sides of the stall ensured that energy leaving through the open end would not be reflected back to interfere appreciably with the field inside. A light source was positioned to one side of the stall in front of the



(a) Side View.



(b) Top view.

FIG. 1. The Stall. The outside length, width, and height of the stall are 1.6, 1.3, and 1.1 meters respectively. The porpoise is shown at the surface but while watching the light and pushing the lever he was at approximately the same depth as the light.

baffle system and a lever-operated switch, A, on the other. A second lever, B, was located on the opposite side of the tank and an automatic fish feeder was positioned adjacent to the stall on the same side as the light.

TRAINING

The experimental animal was a male Tursiops truncatus approximately 8 or 9 years old, named Salty. This animal was 2.3 meters long and weighed about 160 kgm. He was captured in the Gulf of Mexico and had been in captivity about 1 year when the tests were started during the spring of 1964.

Salty was trained, using standard operant conditioning techniques over a period of several weeks, to swim into the stall and watch for the light to come on. When the light was turned on he was trained to push lever A (Fig. 2). In this way the animal was kept in a relatively small area where the sound field could be measured. When he pushed the lever one of three randomly selected events took place: (1) The light was turned off and he waited for it to come on again. (2) The light went off, a buzzer was sounded, and a fish dropped into the tank from the feeder (Fig. 3). The buzzer indicated that he was about to be rewarded, and he would leave the stall to collect his reward and return to watch for the light to come on again. (3) The light went out and a tone was emitted from the sound source. If he detected the tone, he was trained to leave the stall and push lever B on the opposite side of the tank (Fig. 4). He was allowed a period of 12 seconds after the start of the 3-second tone in which to respond. Having done so correctly, a buzzer was sounded and he received his reward from the feeder. His average latency between pushing levers A and B was about 10 seconds so he had only 2 seconds to spare in responding to tones. If he did not hear the tone, he simply waited for the light to come on again. By varying the sound intensity at a given frequency and keeping track of his responses, the threshold could be estimated.

DATA COLLECTION

The data were taken using the staircase or "up-down" method used by Tavolga and Wodinsky (Ref. 8) in their threshold work with fish.

Approximately 1 hour was required to obtain the data required for each threshold determination. The actual data-taking was preceded by a warm-up period of from 15 to 30 minutes. During this period the frequencies and intensities of the tones were varied but with most of the tone intensities well above threshold. No more than two threshold runs were made on a given day. The run ended when the animal had been given sixty reinforcements. Round smelt (Osmerus mordax) running approximately

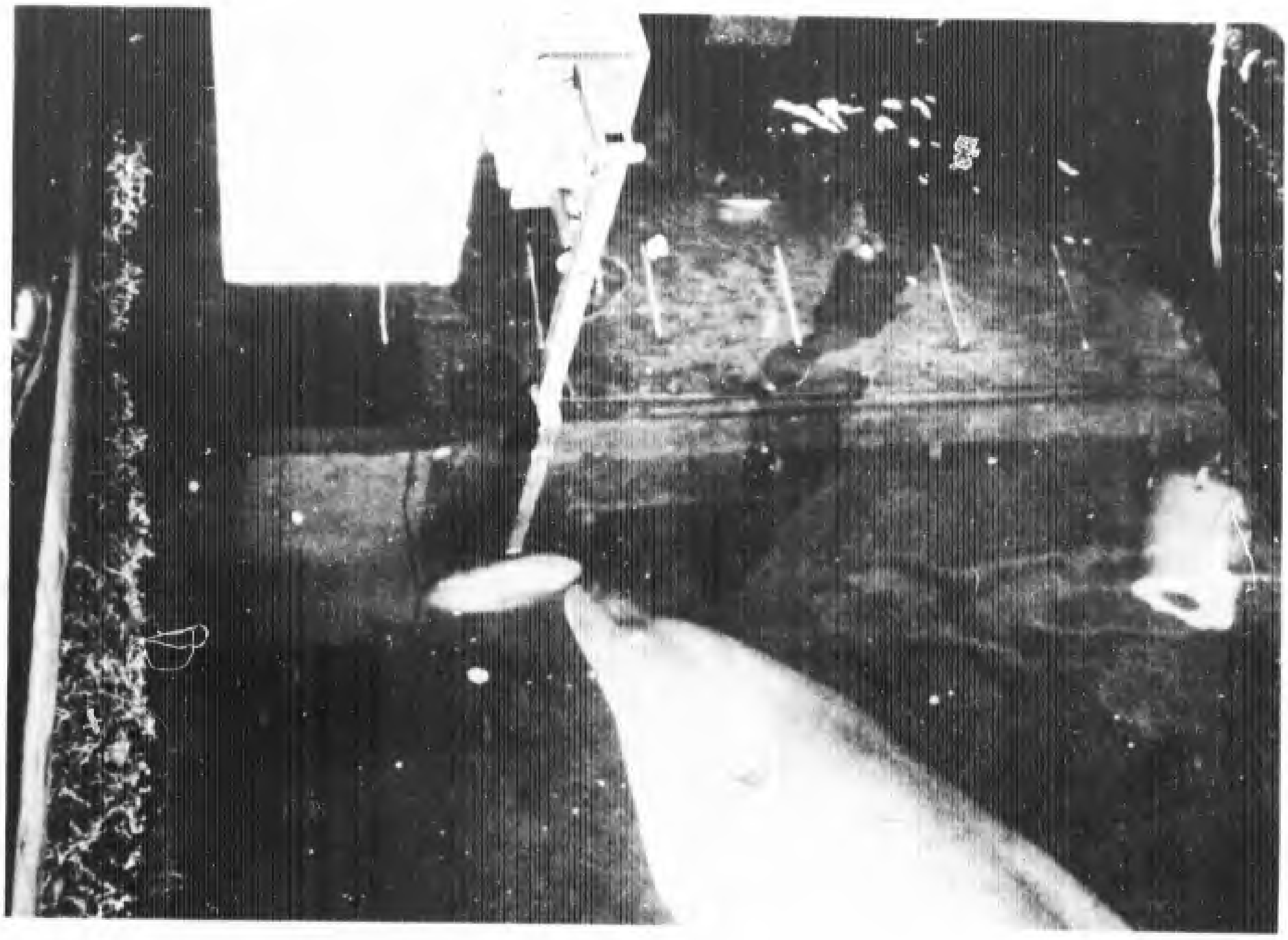


FIG. 2. Porpoise Pushing Lever A. Light is at far right and opening in outer baffle is to the right of the lever.

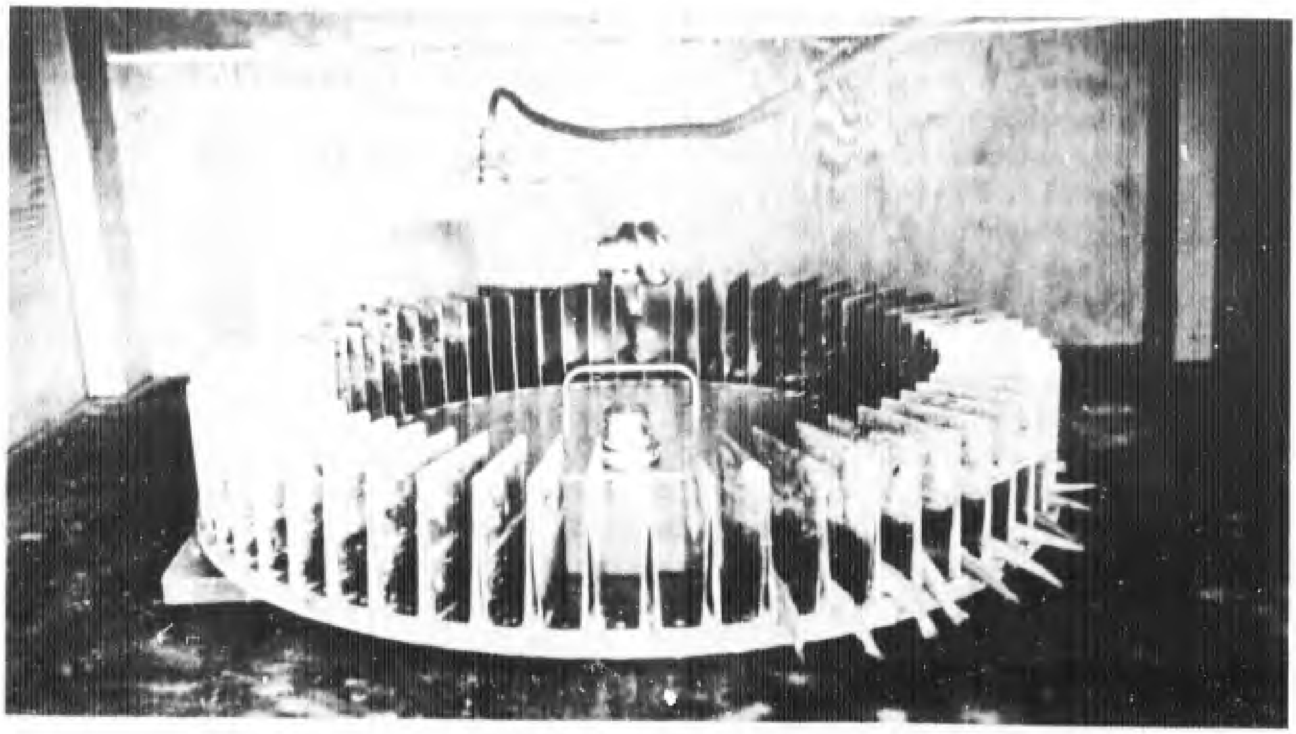


FIG. 3. Rear View of the Automatic Fish Feeder. The motor driven brush pushes the fish out of the slot and they fall through a hole into the tank below. The feeder holds 60 fish.

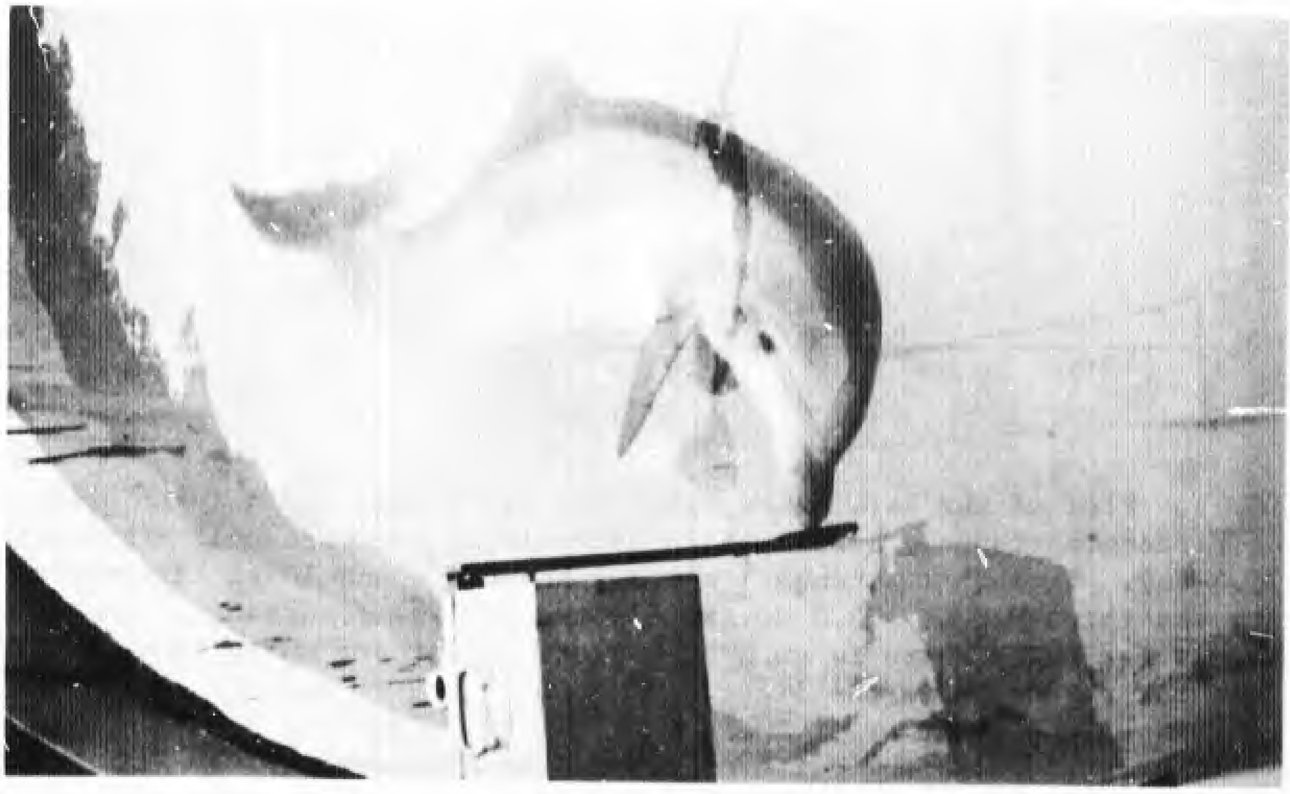


FIG. 4. Porpoise Pushing Lever B.

50 per kgm were used throughout the data taking. He was fed 6.4 kgm each day regardless of performance. In a typical run he would have to respond to the light about one hundred times, received rewards thirty times for doing so and be rewarded an additional thirty times for responding to the tones correctly. This would give about fifty "yes" and "no" responses to the tones. Steps of 1, 2, or 3 decibels were used while taking data. Figure 5 shows a plot of the data taken at 60 kHz. Since he neither received a reward nor tone each time he responded to the light, there was a built-in control against prospecting. However in view of the difficulties in producing a click-free system several other checks were routinely made. The oscillator was sometimes disconnected or switched to a frequency well above or below that to which the band-pass filter was set, and the attenuator was occasionally increased 5 or 10 decibels from the level at which he was responding. Incorrect responses to lever B were rare. When they did occur they were treated as "no" responses in the data analysis.

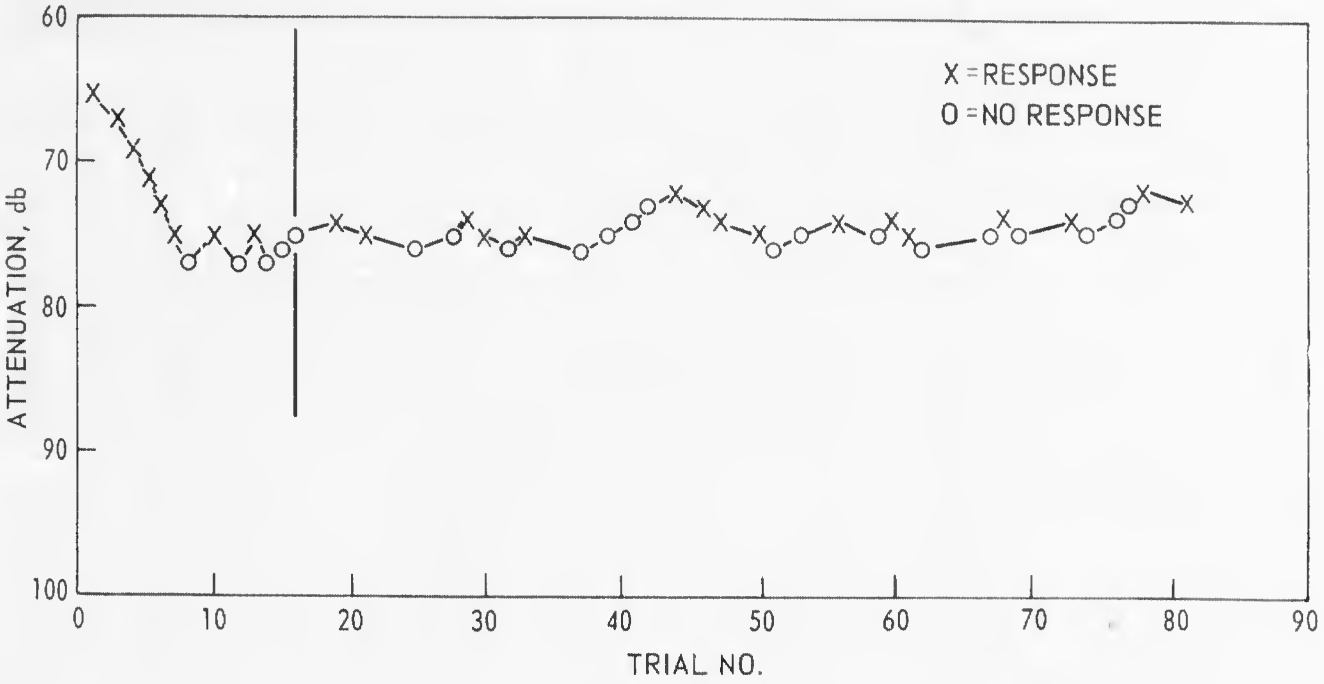


FIG. 5. Plot of the Data Taken (10/7/65) at 60 kHz. Data taken after the fifteenth response were used in determining the threshold attenuation (74.4 db). From this attenuation value and the sound level calibration data the threshold of -55.0 db (re 1 microbar) was determined. The trial numbers for which there is no X or O plotted indicate where rewards were given for responses to the light.

In order to keep the ratio of rewards to responses to the light and tone the same above and near threshold this ratio was varied. If this was not done he would receive considerably fewer rewards when working at intensities near threshold and it proved difficult to keep him working. The ratio was varied by means of a switch in one of the control circuits (see Appendix B). In one switch position a reward was given for every second response to the light for which no tone was sounded. If the animal was responding to every tone (all tone intensities well above threshold) he would, on the average, receive three rewards for every four responses to the light and tones. Two of the three rewards were for responses to the tones. In the other switch position he was rewarded for every response to the light for which no tone was sounded. The switch was used in this position when the sound intensity was near threshold and he was only responding to about half of the tones. In this way he was still rewarded three times for every four responses to the light but two of the three rewards were for responses to the light.

The food consumption per day for this particular animal was determined from a feeding rate study described in Appendix A.

INSTRUMENTATION

With the exception of the tone frequency and intensity, which were controlled manually, the experiment was completely automated electronically. The electronic apparatus (Fig. 6) was housed in a mobile structure adjacent to the tank from which the tests were conducted remotely. The levers were motor driven up and down, and were lowered at the start of an experimental session and raised at the end by remote control. When the animal made an error by pushing lever A when the light was off or lever B when there was no tone he was given a "time-out" and the levers were automatically raised for the duration (90 seconds) of the time-out. On occasion he would stop working and would not enter the stall and watch the light. At such times the levers were raised for a 15-minute time-out.

Three projectors were used. A circular piston barium titanate transducer (Apelco TM-8A), a cylindrical barium titanate transducer (Atlantic LC-10), and a moving coil transducer (J-9 from the Navy Underwater Sound Reference Laboratory, Orlando, Florida). The tone pulse was produced by gating the output of a Hewlett-Packard Model 200CD or 204B oscillator with a Raysistor Model CK1104 photoconducting switch. The turn-on and turn-off times were 20 and 40 msec respectively. The output of the gate went to a Spencer-Kennedy Model 302 band-pass filter, then to a Hewlett-Packard Model 355D attenuator (0-120 decibels) followed by a Kay Model 60-0 attenuator (0-10 decibels), and then to one of the barium titanate transducers. The J-9 was driven by a Hewlett-Packard Model 467A 10-watt power amplifier placed in the circuit after a second 466A amplifier (gain of 20 decibels). A Tektronix Model 502A oscilloscope and a Hewlett-Packard Model 400D vacuum-tube voltmeter were used to continuously monitor the signals going to the projectors. These signals were also checked from time to time using a Panoramic Model SB-15a spectrum analyzer and Hewlett-Packard Models 302A and 315A wave analyzers. A detailed description of the rest of the electronic circuitry is given in Appendix B.

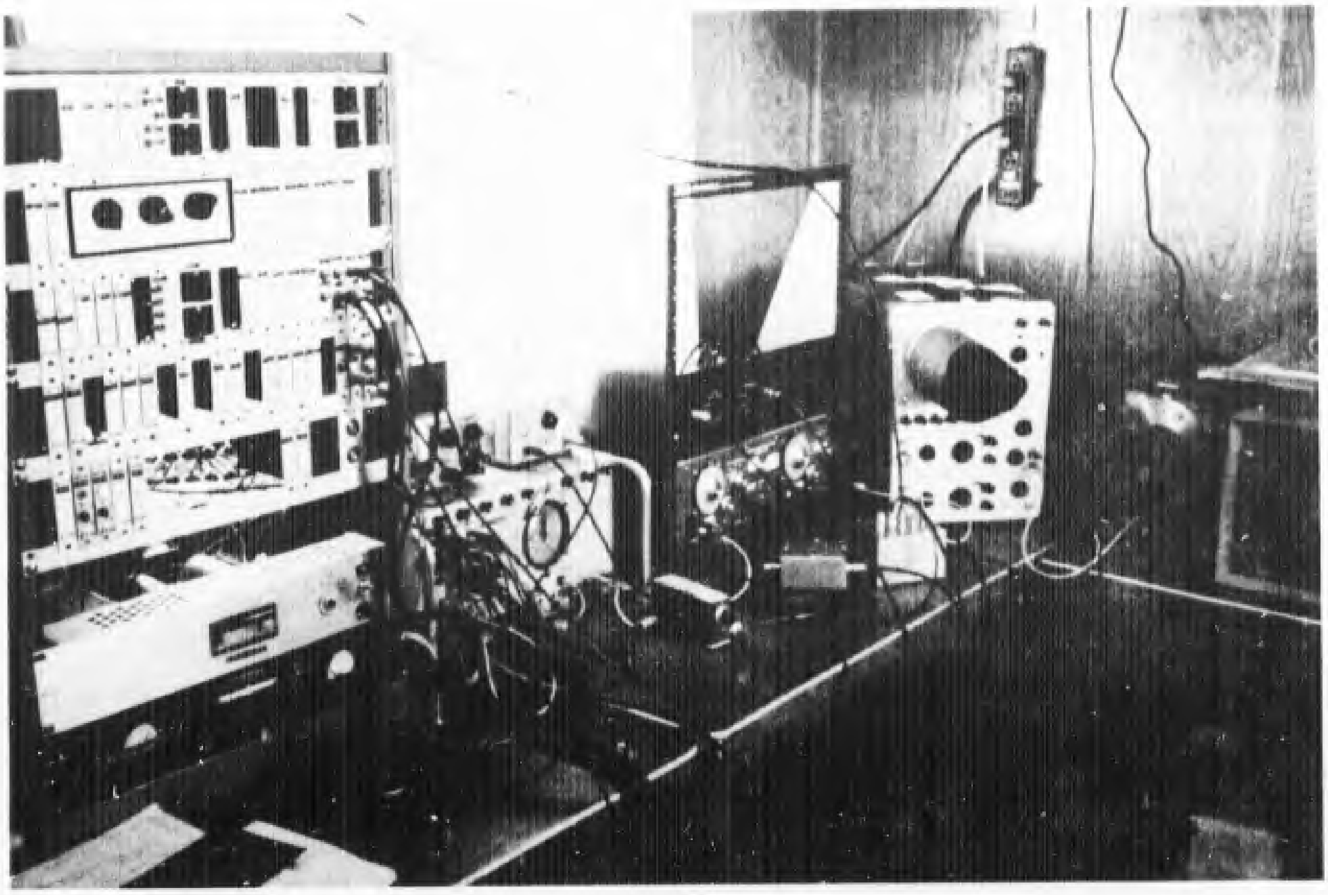


FIG. 6. View of Electronic Apparatus. The rack at far left contains the automatic training circuits described in Appendix B. The automatic feeder control is to the right of the rack. The rack in the center contains the Kay 60-0 attenuator and the Spencer-Kennedy model filter. This is followed by the oscilloscope and oscillator.

CALIBRATIONS

The sound field in the stall was measured at seven locations in the area where the animal's head was located when the tones were sounded. The positions for the two barium titanate transducers were as follows: 31, 46, and 61 cm from the front of the baffle system on the centerline indicated in Fig. 1. Other readings were taken 46 cm in front of the stall, 8 cm above and 15 cm below centerline, and 15 cm to the left and right of centerline. The J-9 was much bigger than the two barium titanate transducers and a hole was cut in the center baffle to make room for it. The J-9 had an over-all length of 28.6 cm, a diameter of 14.4 cm, and a radiating surface diameter of 5.7 cm. Calibration measurements were made with the axis of the J-9 horizontal and 9.5 cm and 24.4 cm back from the front of the baffle system. Measurements were taken at the same seven locations relative to the front of the baffle system as with the two barium titanate transducers, but with a horizontal centerline running through the center of the aperture in the outer baffle. The calibrations were made using an H-17 hydrophone from the Navy Underwater Sound Reference Laboratory. This hydrophone was used with a Massa Model M-185 amplifier power supply and the output signals measured using either a Hewlett-Packard 302A or 315A wave analyzer. The H-17 hydrophone was calibrated over the frequency range from 50 hertz to 150 kHz with a sensitivity of -94 decibels (re 1 volt/microbar) and flat to within ±1 decibel over this frequency range. The results of the calibration measurements are plotted in Fig. 7-9. These figures give the maximum and minimum sound pressures from the seven locations measured. The second harmonic was required to be 40 decibels below the fundamental at the input to the projector at all frequencies in each case.

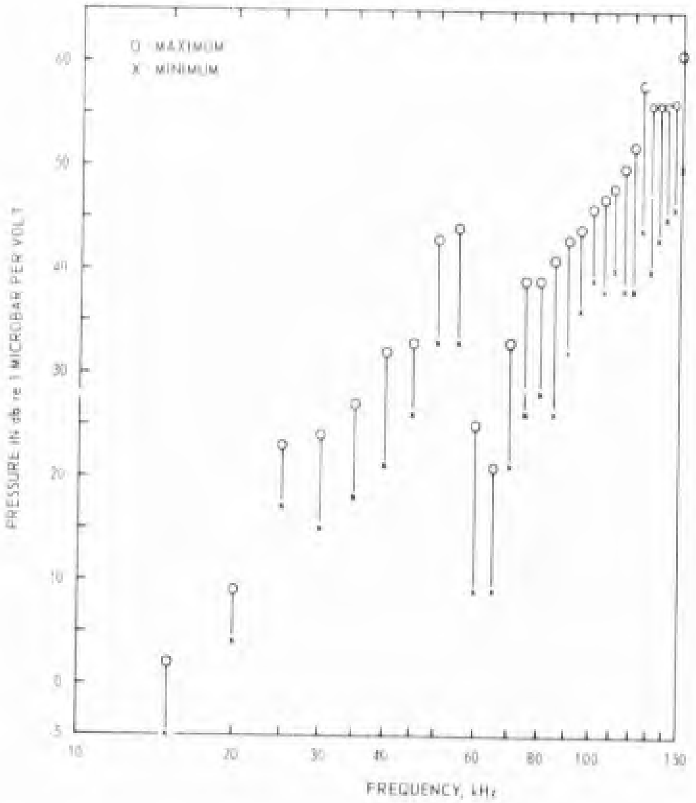


FIG. 7. Output Response of the Apelco TM-8A Transducer. Maximum and minimum sound pressure levels from the seven locations measured.

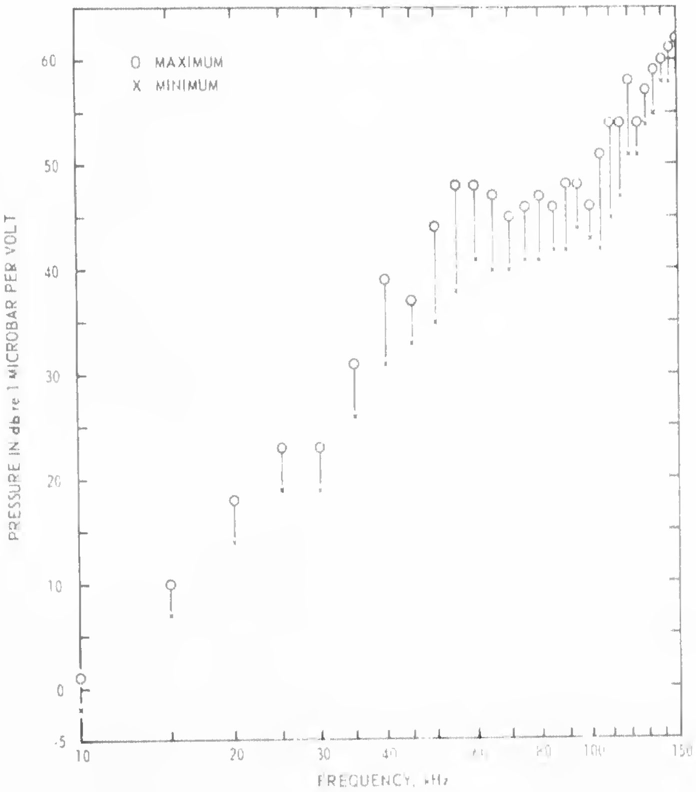


FIG. 8. Output Response of the LC-10 Transducer. Maximum and minimum sound pressure levels from the seven locations measured.

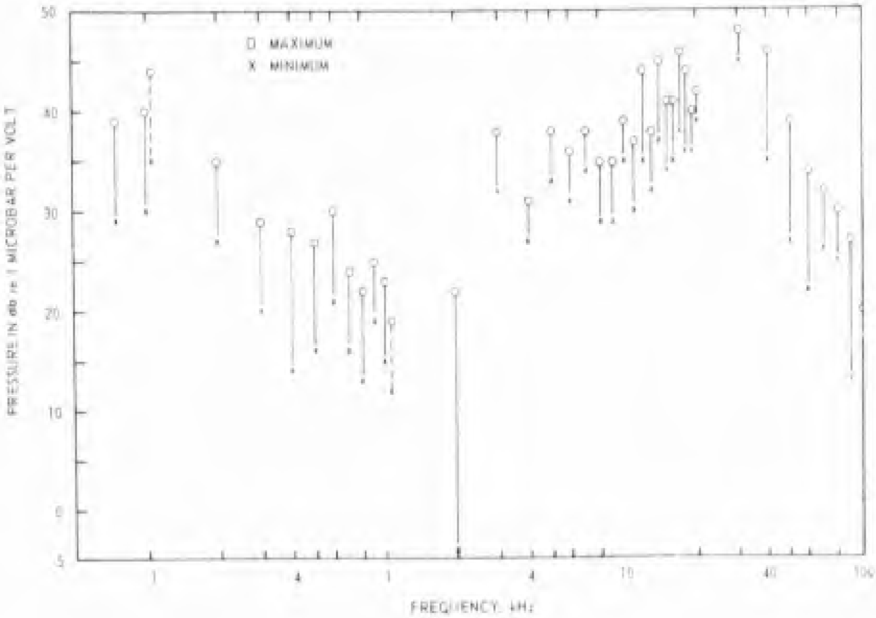


FIG. 9. Output Response of the J-9 Transducer. Maximum and minimum sound pressure levels from the seven locations measured.

The noise in the stall was measured using an AN/PQM-1A noise measuring set and the results of these measurements are given below.

Frequency band, Hz	Noise level	
	db re 1 microbar	db/cycle
100-316	0	-47
316-1,000	-16	-73
1,000-3,160	-17	-84
3,160-10,000	-24	-101
10,000-32,000+	-21	....

RESULTS

The threshold values obtained for the various frequencies are given in Table 1 and plotted in Fig. 10. The statistical uncertainties in these values were computed following Ref. 11. As used the attenuators were somewhat inaccurate and it was necessary to correct the threshold attenuation values to obtain the true values. The correction was obtained by measuring the voltage at the input to the projector with zero attenuation and with the attenuator set at values as close as possible to the threshold attenuation in each case. The voltages were measured with the Hewlett-Packard Models 302A and 315A wave analyzers. From these voltages the true attenuation was calculated. The difference in the calculated attenuations and the attenuator readings give the attenuator corrections.

INTERPRETATION OF RESULTS

In reality what is being measured in this type of experiment is the sound level at which the animal is willing to respond. How closely this approximates the true threshold one cannot say. It is possible that the animal was responding at a level above threshold. It is probably safe to assume that the porpoise had learned that when he responded correctly the level was lowered and when he failed to respond it was raised. Indeed the consistency of the data plotted in Fig. 5 is quite suspicious. Much of the data however did not show this consistency. Nevertheless the question remains. The only way of testing for such artificial effects is to repeat the measurement at a later time and compare results. This was done in many cases and although some of the results agree quite well with one another, there are a few cases where the differences are rather large, one as high as 15 decibels. Much of the scatter in the data in Fig. 10 is probably of behavioral origin, but variation in sound intensity must also contribute to these differences. The remarkable consistency of the data in Fig. 6, whether behavioral or not, seems to indicate that the experimental animal was able to detect changes in level of the order of 1 decibel. Near threshold the differential intensity thresholds in man is 5 or 6 decibels (Ref. 12). An ability to detect small changes in echo intensity would be very valuable in echo-ranging (Ref. 13).

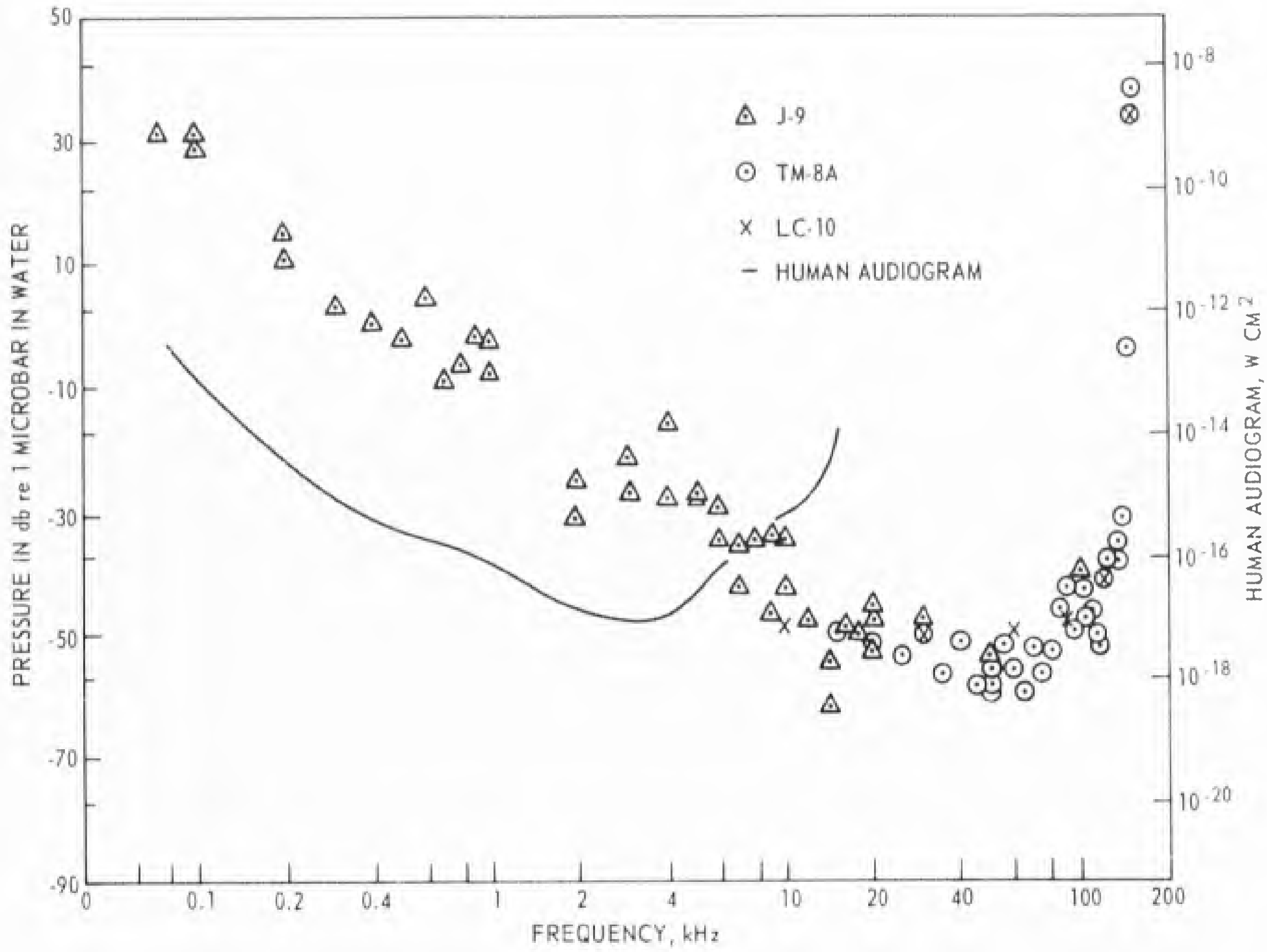


FIG. 10. Audiogram of Threshold Values in Table 1 Compared With Human Audiogram From Ref. 9. The ordinate scale on the left can be converted to decibels (re 0.0002 dyne/cm^2) by adding 74 db. The noise spectrum (not shown) for zero sea state (see Ref. 10) is about 40 db (re 1 microbar) at 100 Hz decreasing with increasing frequency at the rate of approximately 5 db per octave.

TABLE 1. Summary of Auditory Threshold Data

Date tested	Frequency of tone	Step size, db	Trials,[a] no.	T[b]	Threshold, db	σ, db
9/22/65	150 kHz	3	11	24	+37.6[c]	0.5
10/10/65	150	1	14	31	+33.4[c]	1.9
10/25/65	150	1	19	40	+37.6[c]	1.0
12/07/65	150	1	14	31	+33.5[d]	0.6
9/10/65	145	3	14	29	-3.9[c]	1.9
10/19/65	140	1	10	22	-30.5[c]	0.4
9/21/65	135	3	16	33	-34.8[c]	0.5
9/15/65	130	3	12	25	-38.1[c]	0.6
10/05/65	125	2	17	36	-37.7[c]	0.7
9/09/65	120	3	12	26	-40.4[c]	1.0
12/07/65	120	1	17	36	-41.1[d]	1.1
9/24/65	115	2	12	25	-49.9[c]	0.3
10/01/65	115	2	14	30	-50.8[c]	0.7
10/18/65	110	1	12	24	-46.0[c]	0.3
9/21/65	105	3	14	28	-47.0[c]	0.8
9/15/65	100	3	15	32	-41.7[c]	1.5
3/01/66	100	2	20	40	-39.6	0.3
10/04/65	95	2	18	37	-49.2[c]	1.5
10/18/65	90	1	20	40	-42.4[c]	0.5
12/03/65	90	1	11	25	-47.8[d]	0.3
9/24/65	85	3	13	27	-45.4[c]	0.5
10/07/65	80	1	17	36	-52.6[c]	0.4
9/17/65	75	3	8	17	-45.9[c]	0.7
9/13/65	70	3	12	25	-52.1[c]	0.5
10/04/65	65	2	12	29	-59.2[c]	0.5
10/07/65	60	1	15	32	-55.0[c]	0.8
12/03/65	60	1	15	31	-49.0[d]	0.4
9/23/65	55	3	16	33	-51.6[c]	0.4
10/06/65	50	1	16	33	-57.5[c]	0.2
10/21/65	50	1	11	26	-58.3[c]	0.8
10/25/65	50	1	19	39	-55.1[c]	0.3
3/01/66	50	2	16	35	-52.9	0.3
9/17/65	45	3	15	30	-58.0[c]	1.7
9/13/65	40	3	14	29	-50.7[c]	0.6
10/01/65	35	2	16	33	-56.4[c]	0.5

See footnotes at end of table.

TABLE 1. (Contd.)

Date tested	Frequency of tone	Step size, db	Trials, no.[a]	T[b]	Threshold, db	σ, db
10/06/65	30 kHz	1	17	34	-49.5[c]	0.4
12/06/65	30	1	12	28	-49.0[d]	1.0
2/14/66	30	1	18	40	-47.1	0.6
9/23/65	25	3	13	26	-53.2[c]	0.7
10/05/65	20	2	18	36	-51.6	0.2
2/01/66	20	1	14	29	-52.5	0.8
2/10/66	20	1	13	29	-46.7	1.2
2/11/66	20	1	21	45	-45.4	0.3
2/02/66	18	1	18	39	-50.1	0.6
2/02/66	16	1	12	27	-48.4	0.3
9/16/65	15	3	15	30	-49.9[c]	1.4
2/03/66	14	1	14	32	-53.9	1.3
2/10/66	14	1	14	28	-61.4	0.2
2/03/66	12	1	12	29	-47.5	0.9
2/04/66	10	1	12	29	-42.2	0.3
2/11/66	10	1	20	41	-34.0	0.4
12/06/65	10	1	16	34	-48.6[d]	0.4
2/04/66	9	1	16	36	-46.2	0.7
2/14/66	9	1	17	37	-33.8	1.1
2/07/66	8	1	20	40	-34.5	0.3
2/16/66	7	2	13	32	-35.3	1.0
2/28/66	7	2	12	28	-42.2	1.1
2/15/66	6	1	13	29	-29.6	2.0
2/28/66	6	2	14	30	-34.4	0.4
2/09/66	5	2	18	37	-27.3	0.7
2/17/66	5	2	20	41	-26.9	0.4
2/15/66	4	1	10	24	-15.8	0.4
2/27/66	4	2	19	42	-27.7	0.7
2/16/66	3	2	14	33	-21.6	0.6
2/27/66	3	2	21	43	-27.0	0.9
2/17/66	2	2	15	30	-25.3	1.3
2/26/66	2	2	14	31	-30.8	1.0
2/18/66	1	2	18	38	-2.2	1.5
2/26/66	1	2	18	36	-7.8	0.3
3/04/66	1	2	19	39	-1.9[e]	0.4

See footnotes at end of table.

TABLE 1. (Contd.)

Date tested	Frequency of tone	Step size, db	Trials,[a] no.	T[b]	Threshold, db	σ, db
2/22/66	900 Hz	2	25	51	-1.8	0.4
2/25/66	800	2	21	43	-6.3	0.4
2/22/66	700	2	16	35	-8.7	0.6
2/25/66	600	1	15	31	+4.6	0.5
2/18/66	500	2	18	38	-1.7	0.3
2/21/66	400	2	14	29	+0.2	0.5
2/20/66	300	2	14	29	+3.6	0.3
2/20/66	200	2	12	25	+15.5	0.5
2/24/66	200	1	18	39	+10.4	0.8
2/19/66	100	2	15	30	+28.7	0.4
2/24/66	100	2	16	34	+31.7	0.4
3/04/66	100	2	10	23	+31.9[e]	0.7
2/19/66	75	2	18	37	+31.5	0.7

[a] Used to calculate threshold attenuation.

[b] Number of inflection points in threshold determination curve.

[c] Data taken using the Apelco TM-8A transducer.

[d] Data taken using the Atlantic LC-10 transducer.

[e] Data taken with J-9 24.4 cm from the baffle system.

CONCLUSIONS

From Fig. 10 it is concluded that 150 kHz is an effective upper limit to the experimental animal's hearing capability. Considerably lower frequencies were reported by Kellogg (Ref. 4) and Kellogg and Kohler (Ref. 3), 50 and 80 kHz respectively. The results are in much better agreement with those obtained by Schevill and Lawrence (Ref. 5 and 6), who found a sharp cut off above 120 kHz with responses up to 152 kHz. The uncertainty in the sound levels in these experiments do not permit further comparison.

Because the animal knew where and when to listen for the stimulus the conditions of this experiment were similar to those used in human threshold measurements. The minimum audible field audiogram of Sivian and White (Ref. 9) is shown plotted in Fig. 10. As Tavolga and Wodinsky (Ref. 8) pointed out the only meaningful way thresholds in air and water can be compared is on the basis of intensity. Hence the human audiogram has been plotted against the right-hand ordinate in watts per square centimeter. A comparison indicates that the maximum hearing sensitivity of the experimental animal and man are about the same but separated by about 50 kHz in frequency. The data in Fig. 10 give no indication of responses to near-field displacements similar to those observed in fish (Ref. 8). However, it must be noted that the experimental animal had been conditioned to hear rather than "feel" the acoustic stimulus. It is possible that the animal detected the near-field displacements but did not respond to them. The J-9 transducer was in a horizontal position 9.5 cm back from the front of the baffle system for most of the measurements. However thresholds at 100 and 1,000 hertz were measured with the J-9 positioned 24.4 cm from the front of the baffle system. These two values are shown in Table 1 but are not plotted in Fig. 10. The near-field displacements produced at the porpoise's rostrum would be expected to differ considerably at these two positions (Ref. 14). However, the good agreement between the thresholds measured at the two transducer positions indicate that the data were not appreciably affected by near-field displacements.

SUMMARY

Standard operant conditioning techniques were used to train a bottle-nosed porpoise (Tursiops truncatus, Montagu) to respond to pure tone signals by pushing a lever-operated switch. The data were taken by using the staircase method of psychophysics, and an audiogram was obtained over the frequency range from 75 hertz to 150 kHz. The lowest thresholds (greatest hearing sensitivity) occurred in the frequencies near 50 kHz at a level of about -55 decibels (re 1 microbar). Below 50 kHz the threshold level increased (hearing sensitivity decreased) continuously with decreasing frequency to about +37 decibels at 75 hertz. Above 50 kHz the threshold level increased (hearing sensitivity decreased) slowly to about -45 decibels at 100 kHz then more rapidly above 100 kHz to about 35 decibels at 150 kHz. The effective upper limit of hearing for the experimental animal was determined to be 150 kHz. There was no indication of sensitivity to near-field displacements such as those observed in fish. Consistency of some individual threshold data indicate that near threshold the experimental animal could detect differential changes in intensity as small as 1 decibel.

Appendix A

FEEDING RATE STUDY

The progress of many experiments using porpoises is dependent upon the working efficiency of the porpoises and since they work for food rewards it is important to determine as nearly as possible the proper amount of food to give them each day to produce the best working efficiency. The word "efficiency" is used here instead of working rate for the following reasons: Generally, one might expect the highest working rate from an animal when it is hungry and its food drive is high. However, when the animal is hungry it may be too eager to get rewarded and make errors by guessing rather than figuring out the correct responses. In this case experimental results may not be reliable. Then too, if the animal is starved to the point that it loses weight its health may be endangered. On the other hand if the animal is fed too much, its behavior may become erratic because of lack of interest in working for food.

The experimental procedure used to study the animal's feeding rate was quite simple. A lever was positioned on one side of the animal's holding tank and an automatic feeder on the other. The animal was conditioned to push the lever. When it did so a buzzer sounded in the tank, indicating it had pushed the lever properly, and a small fish (smelt) was dropped in the tank by the feeder. There was a 3.5-second delay between the buzzer and feeder operation to allow the porpoise time to reach the feeder before the fish dropped. If the delay was not present the fish would sometimes float to the side of the tank and the porpoise had trouble getting them. This would make the experimental results uncertain since the delay in getting the fish was not under the control of the porpoise or the experimenter. With this arrangement the animal received a reward each time it pushed the lever, and aside from the comparatively small delay (3.5 seconds) between bridging stimulus (buzzer) and feeder, its food intake was governed by the rate at which it pushed the lever. It could push the lever as often as it liked. The number of fish taken was recorded automatically by scalers in a trailer near the holding tank. The total amount of food taken by the animal was varied in a systematic way to determine the best amount to feed the animal day after day to produce the most consistent results. During this work it was important to keep the porpoise as isolated as possible since it was at times easily distracted. Figure 11 gives the data taken on the first day and is representative of the data obtained when the porpoise is allowed to have all the fish he is willing to work for. A point was taken every 5 minutes during the run.

On the 3 days previous to this particular run he had been given 4.6 kgm (10 pounds) of pacific mackerel (Pneumatophorus diego) each day. His intake before then had been held at 8.2 kgm (18 pounds) per day. A straight line has been drawn through the first several points in Fig. 11. The slope of this straight line gives the approximate working rate of the porpoise in reinforcements per minute. His working rate was relatively constant at about 3.6 reinforcements per minute for the first 40 minutes. After this the points depart from the straight line indicating that his rate was slowing down. It is important to note that when this particular run was stopped there were 1 kgm (twenty-one reinforcements) of uneaten fish on the bottom of the tank. He had worked for 11.7 kgm of fish but only eaten 10.7 kgm. What was being determined then was the amount of food to give him to produce a constant work rate (straight line) every day without the decrease in rate shown in Fig. 11. The data collected in this study are summarized in Table 2 and shown plotted in Fig. 12. On some days he was fed part of his ration and worked for the rest. During periods when the animal was given all he would eat (19-25 May and 9-13 July) his food intake fluctuated considerably and on 13 July he would not eat at all. His maximum work rate varied about four reinforcements per minute throughout the testing period indicating that this rate was not very dependent on total food intake. However, if the animal's work rate is to remain constant throughout the day his food intake must be limited. His ration was therefore arbitrarily set in the range of 6.4 to 7.3 kgm. This has proven to be a good choice because he has worked well on this amount of food and his weight has remained stable.

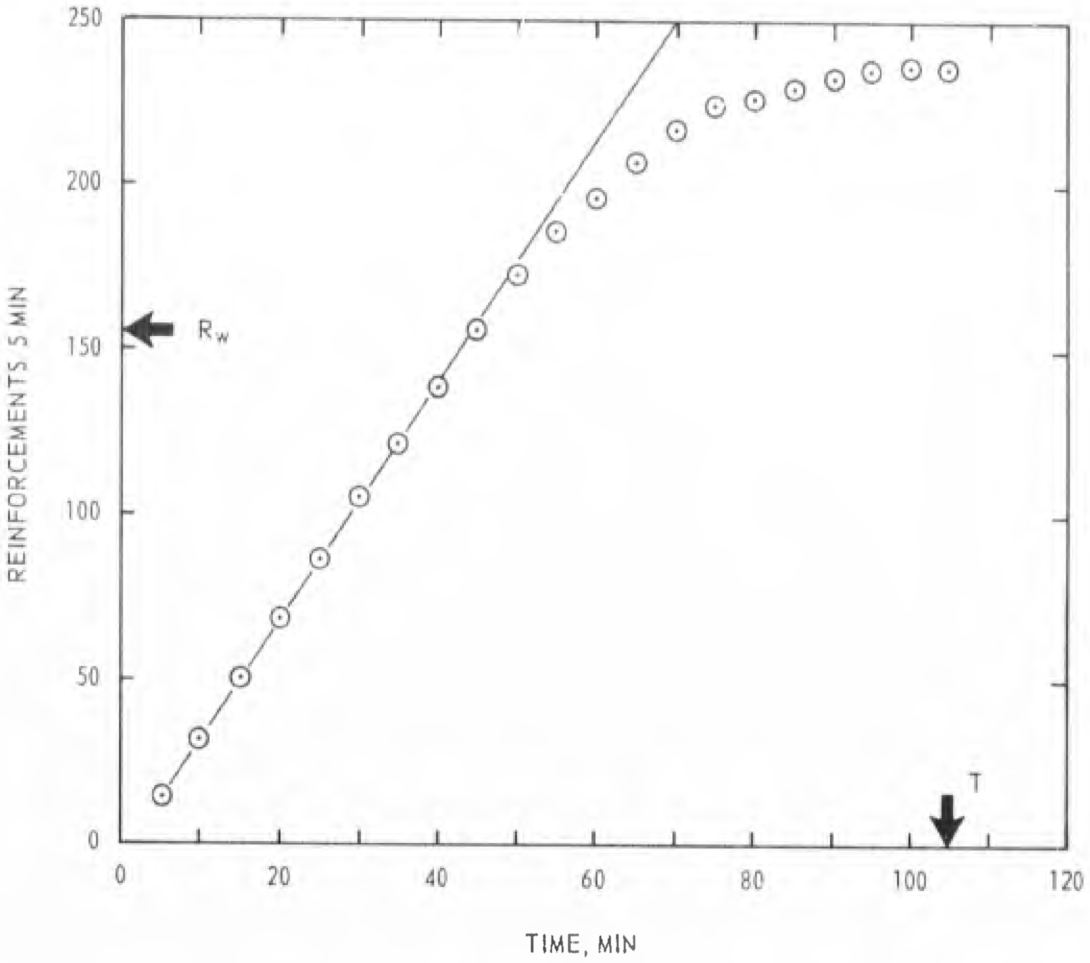


FIG. 11. Plot of Data Taken 5/19/64. R_w indicates the number of reinforcements taken at a constant work rate and T is the duration of the working session. The slope of the straight line gives the work rate, in this case 3.6 reinforcements per minute.

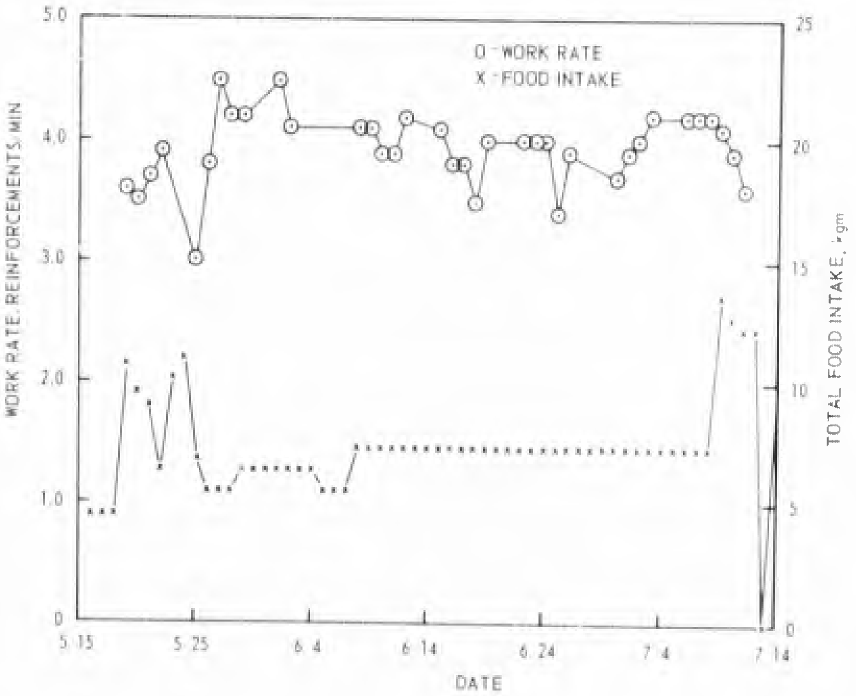


FIG. 12. Summary of the Data Taken During the Feeding Rate Study.

TABLE 2. Summary of Feeding Rate Data

Date	Amount fed 1 hr before session, kgm	Total food intake, kgm	Working session, min	Reinforcements, no.	Work rate, reinforce./min
5/16/64	...	4.5	...	...	...
5/17/64	...	4.5	...	...	...
5/18/65	...	4.5	...	...	...
5/19/64	0	10.7	105	156	3.6
5/20/64	0	9.6	100	156	3.5
5/21/64	0	9.1	70	147	3.7
5/22/64	0	6.4	90	115	3.9
5/23/64	...	10.2	...	...	...
5/24/64	...	10.9	...	...	...
5/25/64[b]	0	6.8	115	82	3.0
5/26/64	0	5.5	90	316	3.8
5/27/64	0	5.5	65	269	4.5
5/28/64	0	5.5	85	353	4.2
5/29/64	0	6.4	95	403	4.2
5/30/64	...	6.4	...	...	...
5/31/64	...	6.4	...	...	...
6/01/64	0	6.4	85	354	4.5
6/02/64	0	6.4	95	390	4.1
6/03/64	...	6.4	...	...	...
6/04/64	...	6.4	...	...	...
6/05/64	...	5.5	...	...	...
6/06/64	...	5.5	...	...	...
6/07/64	...	5.5	...	...	...
6/08/64	0	7.3	100	421	4.1
6/09/64	0	7.3	115	447	4.1
6/10/64	0	7.3	110	441	3.9
6/11/64	0	7.3	110	431	3.9
6/12/64	0	7.3	90	376	4.2
6/13/64	...	7.3	...	...	...
6/14/64	...	7.3	...	...	...
6/15/64	0	7.3	105	430	4.1
6/16/64	1.8	7.3	90	337	3.8
6/17/64	1.8	7.3	90	340	3.8
6/18/64	1.8	7.3	85	303	3.5
6/19/64	1.8	7.3	85	335	4.0

See footnotes at end of table.

TABLE 2. (Contd.)

Date	Amount fed 1 hr before session, kgm	Total food intake, kgm	Working session, min	Reinforcements, no.	Work rate, reinforce./min
6/20/64	...	7.3	...	...	...
6/21/64	...	7.3	...	...	...
6/22/64	2.7	7.3	75	296	4.0
6/23/64	2.7	7.3	70	275	4.0
6/24/64	2.7	7.3	65	260	4.0
6/25/64	5.5	7.3	35	116	3.4
6/26/64	5.5	7.3	30	114	3.9
6/27/64	...	7.3	...	...	...
6/28/64	...	7.3	...	...	...
6/29/64	...	7.3	...	...	...
6/30/64	5.5	7.3	30	110	3.7
7/01/64	1.8	7.3	90	348	3.9
7/02/64	1.8	7.3	85	343	4.0
7/03/64	1.8	7.3	85	353	4.2
7/04/64	...	7.3	...	...	...
7/05/64	...	7.3	...	...	...
7/06/64	1.8	7.3	80	335	4.2
7/07/64	1.8	7.3	65	270	4.2
7/08/64	1.8	7.3	65	275	4.2
7/09/64	1.8	13.6	135	550	4.1
7/10/64	1.8	12.7	140	545	3.9
7/11/64	1.8	12.3	150	531	3.6
7/12/64	...	12.3	...	...	...
7/13/64	...	0	...	...	...
7/14/64	...	10.2	...	...	...

[a] Number of reinforcements taken at constant work rate.

[b] On this date the size of the smelt was reduced from 5/kgm to 14/kgm.

Appendix B

AUTOMATIC TRAINING CIRCUITS

With the exception of the tone frequency and intensity all of the operations experiment were controlled and monitored by the automatic training circuits shown in Fig. 6. The individual circuits were transistorized digital modules and were available commercially (Behavior Research Systems, Beltsville, Maryland). These circuits were found to be very reliable and gave very little trouble during the course of the experiment. The circuitry provided the following operations:

1. It turned on the light for 14 seconds at random intervals that averaged over a long time period about one every 3 or 4 seconds. Individual times could, of course, be 20 seconds or more.

2. It turned off the light when lever A was pushed and randomly presented a tone, rewarded the animal, or turned the light on again.

3. When lever B was pushed within 12 seconds after a tone, a buzzer was sounded and the automatic feeder was operated about 3.5 seconds later. The light was not turned on again for 26 seconds to allow time for the porpoise to get into position again.

4. If lever A was pushed when there was no light or lever B when there was no tone the levers were automatically raised for the duration of the "time-out" and the light did not come on again until after the paddles had been lowered again.

A description of the detailed operation of the circuits would be very difficult to provide here. Instead the more important circuit modules will be listed by number and a brief description of their function will be given. The identifying numbers (circled numbers in Fig. 13) indicates the position of the modules relative to one another in the rack. The circuit designations are those of the manufacturer. As the animal's training progressed and became more complex changes were made in the circuitry. Some of the modules were removed, or replaced, and additional ones added. Hence some numbers are missing and letters have been added to others to indicate their relative positions in the rack.

③ OS-2 (one shot multivibrator) sets the length of the buzzer aignal (1 second).

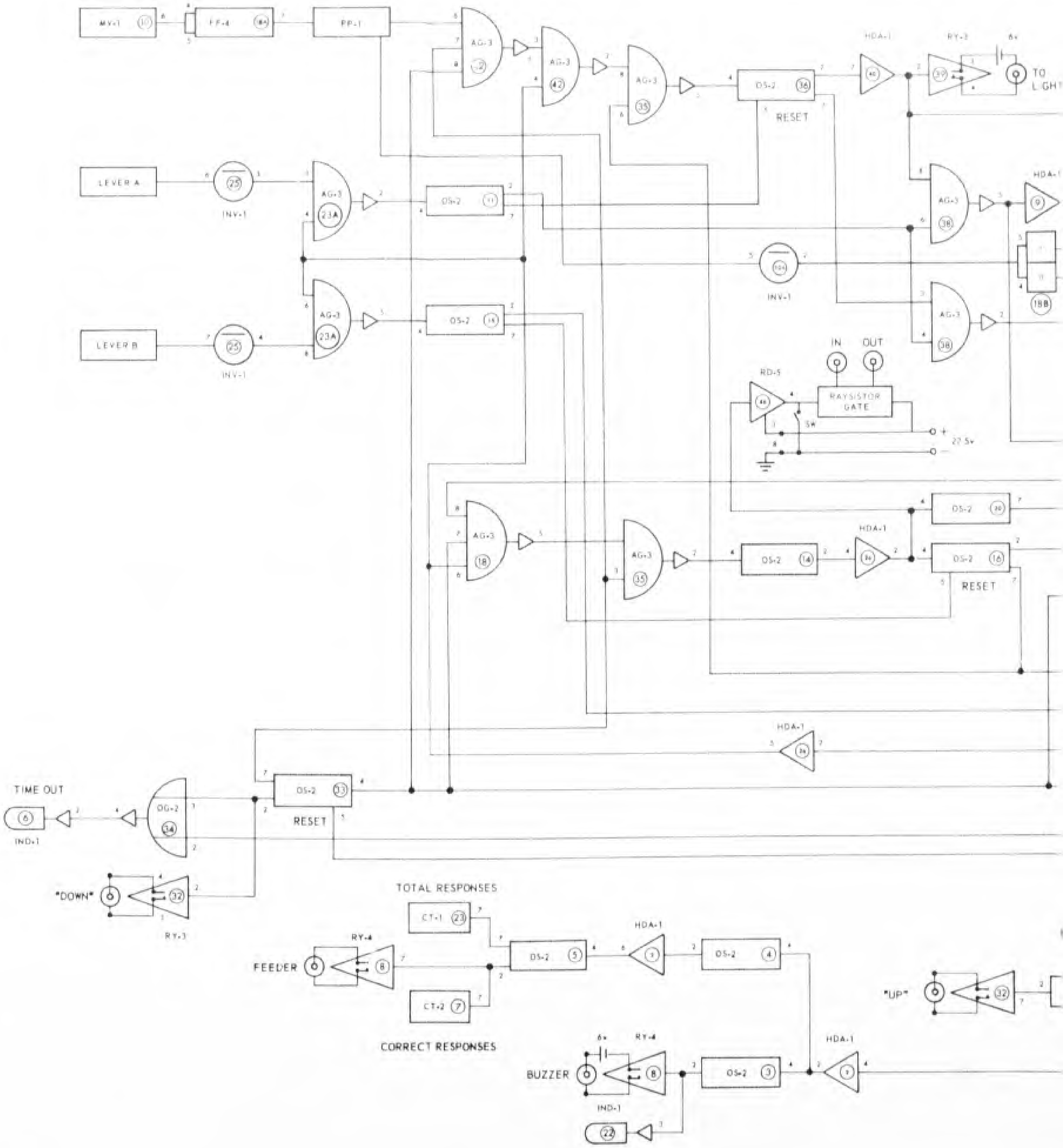
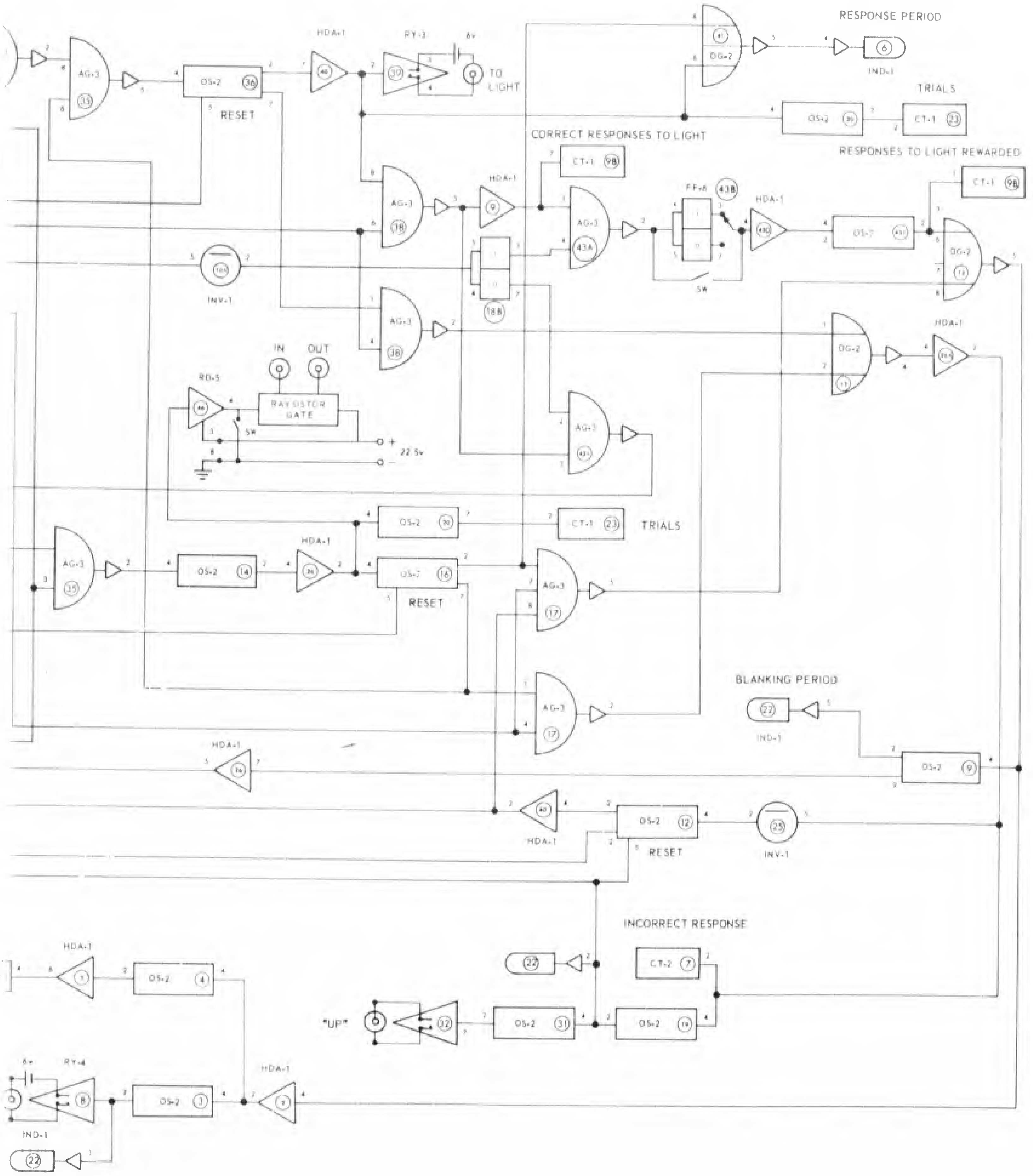


FIG. 13. Schematic Diagram of the Automatic Training Circuits Sh

A



iagram of the Automatic Training Circuits Shown in Fig. 6.

B

BLANK PAGE

④ OS-2 sets the delay between buzzer and feeder operation (3.5 seconds).

⑤ OS-2 operates the relay controlling the feeder.

⑥ IND-1 (4 indicator lights) indicate tone length, length of response periods, correct responses, and length of time-outs.

⑦ CT-2 (2 scalers) record correct and incorrect responses.

⑧ RY-4 (2 relays) operate the buzzer and the automatic feeder.

⑨ OS-2 sets the length of the blanking period after a correct response to allow the animal to get into position again (26 seconds).

(9B) CT-2 records the correct responses to the light (C.R.L.) and the responses to the light that are rewarded (R.L.R.).

⑩ MV-1 (free running multivibrator) plus 18A (FF-4 bistable multivibrator) produce 1 hertz train of pulses for PP-1. PP-1 (precision probability unit) is a circuit which produces at its outputs a fraction, adjustable from 0 to 0.99, of the imput pulses with random intervals between them. In this case the ratio of output to input of pulses from PP-1 was always 0.3 when taking data.

⑫ OS-2 sets length of time-outs.

⑭ OS-2 sets length of tones.

⑯ OS-2 sets length of response period (R.P.) for responses to tones.

⑰ AG-3 (2 AND gates) determine correct and incorrect responses to tones.

⑱ AG-3 is used to stop tones from being initiated during time-outs, and correct and incorrect responses.

(18B) FF-4 randomly selects with 42A which responses to the light produced tones.

㉒ IND-1 indicates blanking period set by ⑨, delay between buzzer and feeder, and length of time buzzer is on.

㉓ CT-1 counts the number of times the light goes on (trails) and the total number of correct responses during the day.

(23A) AG-3 stops pulses from levers A and B after correct responses.

㉔ OS-2 resets the time out OS-2 ⑫ and the OS-2 controlling the "down" relay ㉝ so that "up" and "down" relays are not used simultaneously.

㉕ INV-1 (inverters) used to drive OS-2's for levers A and B and delay start of time-out OS-2 ⑫ so that it can be reset before a start pulse comes from PP-1. In this way additional error response will start the time-out period over again.

㉛ OS-2 set the period for the "up" relay.

㉜ RY-4 (two reed relays) operates heavy duty relays which drive paddles up and down.

㉝ OS-2 sets the period for the "down" relay.

㉞ OG-2 (OR gate) mixes pulses from ㉝ and ⑫ going to the time-out indicator light so that the correct time-out, including time to lower the levers is indicated by the light.

㉟ AG-3 stops light from coming on during response period for tone and stops any possibility of a tone being initiated by an incorrect response during a time-out.

㊱ OS-2 sets the length of the period the light is on.

㊳ AG-3 determines correct and incorrect responses to the light.

㊴ RY-4 operates the light.

㊷ AG-3 stops light from coming on while paddle is being lowered and during blanking period.

(42A) AG-3 selects which responses to the light produce tones.

(43A) AG-3 selects which responses to the light do not produce tones.

(43B) FF-6 with by-pass switch closed allows rewards each time the light is responded to and no tone is sounded or with switch open rewards every second "no tone" response to the light.

REFERENCES

1. Kellogg, Winthrop N. Porpoises and Sonar. Chicago, Univ. of Chicago Press, 1961, P. 82.

2. Slijper, E. J. Whales. New York, Basic Books, 1962. Chap. 7.

3. Kellogg, W. N., and R. Kohler. "Responses of the Porpoise to Ultrasonic Frequencies," SCIENCE, Vol. 116 (1952), pp. 250-52.

4. Kellogg, W. N. "Ultrasonic Hearing in the Porpoise," J COMP PHYSIOL PSYCHOL, Vol. 46 (1953), pp. 446-50.

5. Schevill, W. E., and B. Lawrence, "Auditory Response of a Bottlenosed Porpoise, Tursiops truncatus, to Frequencies Above 100 kc," J EXPL ZOOL, Vol. 124 (1953), pp. 147-65.

6. ------. "High-frequency Auditory Response of a Bottlenosed Dolphin, Tursiops truncatus (Montagu)," ACOUST SOC AM, J, Vol. 25 (1953), pp. 1016-17.

7. Norris, K. S., J. H. Prescott, P. V. Asa-Dorian, and P. Perkins. "An Experimental Demonstration of Echolocation Behavior in the Porpoise, Tursiops truncatus (Montagu)," BIOL BULL, Vol. 120 (1961), pp. 163-76.

8. Tavolga, W. N., and J. Wodinsky. "Pure Tone Thresholds in Nine Species of Marine Teleosts," AM MUSEUM NAT HIST, BULL, Vol. 126 (1963), pp. 179-239.

9. Sivian, L. J., and S. D. White. "On Minimum Audible Sound Fields," ACOUST SOC AM, J, Vol. 4 (1933), pp. 288-321.

10. Mellen, R. H. "The Thermal-Noise Limit in the Detection of Underwater Acoustic Signals," ACOUST SOC AM, J, Vol. 24 (1952), pp. 478-80.

11. Dixon, W. J., and F. R. Massey, Jr. Introduction to Statistical Analysis. New York, McGraw-Hill, 1951. Chap. 19.

12. Stevens, S. S., and H. Davis. Hearing. New York, Wiley, 1938.

13. Grinnell, A. D. "The Neurophysiology of Audition in Bats: Intensity and Frequency Parameters," J PHYSIOL, Vol. 167 (1963), pp. 38-66.

14. Harris, G. H., and W. A. Van Bergeijk. "Evidence that the Lateral-line Organ Responds to Near-field Displacements of Sound in Water," ACOUST SOC AM, J, Vol. 34 (1962), pp. 1831-41.

INITIAL DISTRIBUTION

- 4 Naval Air Systems Command
  - AIR-604 (2)
  - R-12 (1)
  - RRRE-1 (1)
- 4 Chief of Naval Operations
  - Capt. Lawrence K. Savadkin (1)
  - LCdr. R. G. Reed (1)
  - Dr. Robert O. Burns (1)
  - OP-702 (1)
- 9 Chief of Naval Material
  - RAdm. I. J. Galantin (1)
  - Cdr. L. L. Jackson (1)
  - Cdr. F. R. Haselton (1)
  - Dr. Samuel Rotham (1)
  - Murray H. Schefer (1)
  - Sp-00 (1)
  - Sp-001 (1)
  - Sp-003 (1)
  - Sp-20 (1)
- 2 Naval Ship Systems Command
  - SHIP-0354, Cdr. George Devilbliss (1)
  - SHIP-03542, Cdr. Richard H. Gaunt (1)
- 5 Office of Naval Research
  - Capt. L. B. Melson (1)
  - Dr. Edward M. Nelson (1)
  - Dr. J. N. Adkins (1)
  - Dr. Roger D. Reid (1)
  - Code 446, Helen L. Hayes (1)
- 3 Naval Missile Center, Point Mugu (Marine Bio-Science Facility)
  - Code 5353
    - Dr. S. H. Ridgway (1)
    - F. G. Wood, Jr. (1)
    - L. Padberg (1)
- 1 Navy Underwater Sound Reference Laboratory, Orlando
- 1 Office of Naval Research Branch Office, Pasadena (Dr. John B. Loefer)
- 1 Office of Naval Research Branch Office, San Francisco (Dr. M. P. Wennekens)
- 1 Underwater Demolition Team 12 (Capt. Bucklew)
- 1 Office of Naval Research Resident Representative, La Jolla
- 2 Chief of Staff, U.S. Army
  - Biological Sciences Branch (1)
  - Special Projects Branch (1)

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY *(Corporate author)* U. S. Naval Ordnance Test Station China Lake, California 93555	2a REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP

3 REPORT TITLE

AUDITORY THRESHOLDS OF THE BOTTLENOSED PORPOISE (TURSIOPS TRUNCATUS, MONTAGU)

4 DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Research Report

5 AUTHOR(S) *(Last name, first name, initial)*

Johnson, C. Scott

6 REPORT DATE November 1966	7a TOTAL NO. OF PAGES 28	7b. NO. OF REFS 14

8a CONTRACT OR GRANT NO. b. PROJECT NO. c BuWeps Task Assignment R360-FR-106/216-1/R011-01-01 d.	9a ORIGINATOR'S REPORT NUMBER(S) NOTS TP 4178 9b OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10 AVAILABILITY LIMITATION NOTICES

Distribution of this document is unlimited.

11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY Director of Laboratory Programs Naval Material Command Washington, D. C. 20360

13 ABSTRACT

Standard operant conditioning techniques were used to train a bottlenosed porpoise to respond to pure tone signals by pushing a lever-operated switch. An audiogram was obtained over the frequency range from 75 hertz to 150 kHz. The lowest thresholds (greatest hearing sensitivity) occurred in the frequencies near 50 kHz at a level of about -55 decibels (re 1 microbar). The effective upper limit of hearing for the experimental animal was determined to be 150 kHz. There was no indication of sensitivity to near-field displacements such as those observed in fish.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Auditory thresholds Porpoise, bottlenosed; auditory thresholds of *Tursiops truncatus*, Montagu; auditory thresholds of						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_______________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_______________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_______________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.