REACTIONS OF FISH
TO VARIOUS INTENSITIES OF DIRECT CURRENT ELECTRICITY
IN WATERS WITH DIFFERENT CONDUCTIVITY

By

PIERRE CHESTER LAWSON

Bachelor of Science

University of Omaha

Omaha, Nebraska

1945

Submitted to the Faculty of the Graduate School of
the Oklahoma Agricultural and Mechanical College
in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE
May, 1953

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THESIS AND ABSTRACT APPROVED:

W. H. Irwin
Thesis Adviser

F. M. Baumgartner
Faculty Representative

Dean of the Graduate School

ACKNOWLEDGEMENT

The writer is indebted to his adviser, Dr. William H. Irwin, upon whose suggestion this problem was chosen and with whose help and guidance the same was carried to completion. He also wishes to thank J. Lowell Cawood, whose suggestions in the solution of the electrical technicalities of the problem were invaluable.

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I. INTRODUCTION

The data presented herein is the result of an investigation of the reactions of certain fish to the stimulus of direct current electricity with attention concentrated upon determination of the voltages which would result in optimum galvanotropism in waters characterized by a range of resistances. The study was done with the Zoology Department of Oklahoma A. and M. College, Stillwater, Oklahoma, under the supervision of Dr. W. H. Irwin during the year of 1952.

The advantage of using direct current over alternating current to sample fish populations seems apparent. The general conclusions summarized from the literature indicates that alternating current requires less power to stun a fish, it requires less equipment, and it is not as dangerous to humans. Direct current is much less harmful to fish as it affects a narcosis rather than a tetanus plus possible torn muscles or vertebrae. The fact that direct current is much less harmful than alternating current enables a higher direct current potential to be used, thus permitting a greater area to be sampled at one time than is possible with alternating current. The evidence that direct current results in a concentration of fish at the positive electrode is the most significant reason for its choice over alternating current in this study.

Literature treating the effects of direct currents on fish is scanty and any mention of voltages in relation to conductivity of water is slight or nil. The following authors had this to say regarding the potential intensity in relation to galvanotropism. Elson (1950) working with fresh water found that a gradient of about three volts per inch was sufficient to stun all fish over three inches long, while one to two volts per inch stimulated smaller fish and frequently stunned fish over five inches long. Houston (1949) in his description of Kreutzer's experiment in sea water stated that several experimenters had recorded that the usual commercial fish reached a state of electrotaxis with a potential of 0.5-1.5 volts between head and tail. Regarding water resistance in association with power requirements, the following information was found. Concerning Kreutzer's experiment, Houston (1949) remarks that because of the low resistance of sea water, the pulse voltage will not be great, but the peak current can be about 10,000 amperes. Peglow (1949) also considering marine experiments mentions that electronic laws apply in the conversion of technical data from fresh to salt water and that the consumption of power in the latter is greater but the physiological effects are more favorable. Denzer (1949) states that a greater amount of electrical energy is needed to successfully stimulate fish in salt water than in fresh water. Referring to fresh water, Fisher (1950) declares that a change in the resistance of water affects the electrical power consumed ② without affecting the voltage drop per foot; Elson (1950) maintains the power requirement in fish shocking is proportional to the conductivity of the water; Burr (1931) stated that a fish offers greater resistance to an applied current than does the water and its dissolved minerals, and that the greater the amount of dissolved mineral in the water, the less is the effect of the current on the fish; but Haskell (1952) found that "fish flesh has a lower electrical resistance than most water." In the present study an attempt has been made to learn the voltage necessary to stimulate fish to galvanotaxis in waters representing different conductivities. To date no literature has been found that treats specifically with the problem.

II. METHOD

The fish used were Crappie, Bluegill, Redear sunfish, Green sunfish, Longear sunfish, Black bullheads, and Fathead minnows. The trials were made in two aquaria, one 12 by 24 inches and the other 6 by 18 inches, using electrodes of copper window screen which covered both ends of each aquarium. Forty telephone batteries connected in series were used where low voltages and a heavy current was required. Two rectifier power supplies having ranges of 0-180 and 0-550 volts were used for higher potentials. On a panel board were mounted a voltmeter to measure the potential at the copper screens, and an ammeter to measure the current through the water between the electrodes; a reversing switch to reverse the polarity of the electrodes; and terminal posts to facilitate the connections of different components. A sensitive volt-ohm-ammeter was used as a standard for accurate reading. A telegraph key was used as the switch with which to apply the impulses as a stimulus to the fish. A centigrade thermometer was used when records were made of the water temperature in the aquarium. Holding tanks were maintained to provide a supply of fish for the experiments. A device for measuring resistance of water was made consisting of two metal pegs mounted two inches apart on a composition insulation block 3/8 by 3/4 by 3 inches. The pegs protruded from the block with leads soldered to the short ends. The leads were attached to an ohmmeter and the pegs immersed in the water to read the resistance. This crude ohmmeter resulted in readings that, although not standard, were time saving and served to give comparative resistances of the different waters. Later a standard resistance bridge having a range of 0.00002-250 kilohms was available for measuring the water resistances. Tap water, distilled water, and salts were mixed in proportions to obtain the desired resistances.

A 1000-volt dynamotor driven by a gasoline motor generator was used as a power source in the field trial. An eight-foot square dip net was used beneath the positive electrode for the purpose of collecting the fish. The positive electrode of quarter-inch mesh copper hardware cloth was placed parallel to the negative electrode. The negative electrode consisting of a twenty-foot cable with bare weighted copper wires suspended at four-foot intervals was stretched across the pond forty feet from the positive electrode. A telegraph key was used as a switch to apply the low voltage to energize a relay which applied the thousand volts of the dynamotor to the electric seine. Two meters were permanently wired in the seine circuit for continuous reading of voltage and current.

III. PROCEDURE

The laboratory experiments were first made in the 12 by 24 inch aquarium by steps, which follow.

1. Wire connections were made between the panel board, power supply, and electrodes; the resistance of the water was read; and the rheostat adjusted to regulate the voltage.
2. A fish was placed in the aquarium and impulses of electricity were applied by means of quick taps on the telegraph key.
3. The reactions of the fish were observed and recorded along with the water resistance, the potential, and the current. The procedure was repeated with the same water resistance but with a different fish and a different potential. The range of voltages used varied from a potential below that which caused a threshold of stimulus to a high potential that narcotized the fish. In this way it was hoped that the voltages which produced galvanotaxis could be determined. The water resistance was re-read frequently, because some change was caused even by the process of exchanging the fish.
4. The resistance of the water was changed, measured, and the water level returned to its previous position in the aquarium before the above steps in parts 2 and 3 were repeated.

Distilled water was used for early experiments because of its high resistances. Then tap water was added in increasing amounts to produce lower resistances. After several trials, the need for more power per volume of water became apparent. The problem was minimized by using the smaller (6 by 18 inch) aquarium which better met the capacity of the rectifier power supply. The Fathead minnow was then used so that a larger number of fish could be stimulated at one time in the reduced water volume. Three or more fish were used rather than one only, and steps 1 through 4 were repeated as with the larger aquarium.

Later the 0-550 volt power supply was built which extended the range of resistances that could be studied. Experiments involving minnows were repeated until a series of water resistances ranging from a high of 230,000 ohms to a low of 104 ohms were used.

IV. DISCUSSION

Ignorance (1) of the nature of definite responses of fish to direct current stimuli, (2) of the potential and current needed per volume of water, (3) of the nature of the electric field in the water, (4) of the effect of the applied impulse to fish in waters of different resistances, resulted in the performance of many experiments that seemed meaningless or contradictory in results at the beginning.

First, a stimulus that produced galvanotropic-like responses had to be found. Although galvanotropism has been used, for the lack of a better term, to describe the response in which fish when stimulated move toward the positive electrode, it is the writer's opinion that the reaction is a reflex. Harreveld (1938) and Haskell (1952) seem to support the contention. Because a limited supply of power (198 volts) was available, distilled water was used in early trial, but the range of potentials possible with the supply failed to produce galvanotropic responses. It was necessary to decrease the resistance before desired responses were procurred. Thus a beginning point of reaction was established. A gradual increase or decrease of either voltage and resistance produced additional tropic responses.

Second, from Ohm's law, if the water volume and power are held constant but the conductivity is increased, the current will be increased and the voltage decreased, and when the conductivity is decreased, the current will be decreased and the voltage increased. If the conductivity of the water is constant and the volume of the water between the electrodes is increased, the power applied must be increased to maintain a constant voltage and current. Herein no effort was made to hold the power applied to the electrodes constant, but additional power was necessary when increased current caused by decreased water resistance lowered the voltage below the potential necessary for galvanotropic responses. It was also noted that when the electrodes were farther apart higher voltages were needed to produce galvanotropic responses in fish. When the lack of power became apparent, the smaller aquarium and a larger power supply (550 volts) were used.

Third, the nature of flow of electrical current through water is still speculation. If the current were passing through a wire of uniform construction and size, the flow would be uniform throughout. But an electric current flowing through water between two electrodes of equal size would not necessarily be bounded by a uniform area even though there be uniform conductivity and the bottom soil non-conductive. Therefore, it seems possible that the flow (per cross-sectional area) would be strongest near the electrodes and weakest at midpoint between the electrodes and that the field of flow would tend to spread in the water between the electrodes. If this speculation be true, the electric field will not be uniform, and a voltage increase to electrify a greater distance will not necessarily increase the flow (per cross-sectional area) in a linear proportion. In laboratory experiments, screen electrodes covered the ends of the rectangular aquarium to produce as uniform a field of current as possible.

Fourth, the data resulting from the experiments done in the large aquarium (Table 1) was organized according to the reaction of each kind of

Table 1. Reactions of several kinds of fish to direct current impulses in a 12 by 24 inch aquarium, with the water resistance, the voltage used, the current produced, and the length of the fish.

Species of Fish	Water Resistance in Kilohms	Volts Applied	Milli-amperes	Fish Length in Inches	Reactions
Redear sunfish	2.9	3.5	6.0	6.0	**
	3.0	3.5	17.0	6.0	**
	2.8	18.0	38.0	---	****
	3.0	22.0	60.0	5.0	****
	2.5	24.0	80.0	6.0	****
	17.0	30.0	11.0	5.0	****
	15.0	23.0	12.0	5.0	*****
	3.1	30.0	290.0	---	*****
	650.0	120.0	9.0	6.5	*****
	900.0	120.0	9.0	---	*****
Longear sunfish	7.0	12.0	6.8	5.0	*
	2.8	3.5	6.1	6.0	**
	2.8	10.0	21.0	6.0	**
	13.0	20.0	8.0	5.0	**
	2.8	17.0	36.0	5.0	****
Black bullhead	150.0	2.6	0.1	7.0	*
	20.0	20-40	3.0	7.5	*
	60.0	40.0	3.4	6.5	*
	2.8	3.0	6.0	6.0	**
	2.8	4.6	9.6	6.0	**
	40.0	14.0	1.4	7.0	**
	3.0	3.0	5.9	7.0	***
	8.6	6.0	2.4	7.5	***
	9.5	6.0	2.4	7.5	***
	9.0	12.0	2.4	6.5	***
	3.1	45.0	120.0	6.5	***
	150.0	16.0	0.8	7.0	****
	3.0	17.0	36.0	7.0	****
	17.0	19.0	---	---	****
	2.8	20.0	---	7.0	****
	3.1	23.0	80.0	8.0	****
	3.1	30.0	130.0	6.5	****
	3.1	30.0	290.0	6.0	****
	3.1	34.0	130.0	6.5	****
	60.0	54.0	4.4	6.5	****

Table 1. (Continued)

Species of Fish	Water Resistance in Kilohms	Volts Applied	Milli-amperes	Fish Length in Inches	Reactions
Bluegills	2.8	3.0	5.6	6.0	**
	2.8	3.0	6.0	5.0	**
	2.8	3.4	6.5	7.0	**
	2.8	4.5	9.0	7.5	**
	30.0	12.5	1.1	---	**
	40.0	14.0	1.4	---	**
	75.0	16.0	1.0	---	**
	3.0	17.0	36.0	---	****
	2.8	20.0	---	---	****
	40.0	180.0	23.0	3.0	****
	42.0	180.0	21.1	4.0	*****
	42.0	180.0	21.1	5.0	*****
	60.0	186.0	15.0	4.5	*****
Green sunfish	24.0	1.5	2.0	5.0	*
	24.0	3.0	nil	5.0	*
	24.0	4.6	0.75	5.0	*
	24.0	8.0	1.0	5.0	*
	24.0	9.5	1.2	5.0	*
	24.0	19.0	2.8	5.0	*
	20.0	20-40	7.5	4.5	*
	17.0	19.0	4.0	5.0	**
	100.0	51.0	2.6	6.0	**
	17.0	12.0	4.8	5.5	****
	17.0	25.0	10.0	5.5	****
	15.0	25.0	12.0	5.5	****
	17.0	12.0	4.8	5.5	*****
	100.0	100.0	4.0	6.0	*****
	42.0	180.0	21.1	5.5	*****
	60.0	186.0	17.0	6.5	*****

*	No reaction evident in fish.
**	Threshold--fish stimulated but did not move toward the positive electrode.
***	Weak galvanotropic response.
****	Good galvanotropic response.
*****	No galvanotropic response, fish were caused to dart first one direction and then another, or were stunned.

fish in the following order: no reaction evident; threshold, in which the fish was stimulated but did not move toward the positive electrode, and made a slight movement of the tail or the fin in response to the impulse; weak galvanotropic response; good galvanotropic response; and excessive reaction in which the fish darted back and forth between the electrodes, or abruptly ceased movement and were stunned. Within each of these categories, the data were arranged from low to high voltages. It was also noted that at stunning potentials the melanophores disappeared even to the extreme ends of the fins. The fish would recover from stunning, and the melanophores reappear unless the impulses were continued to a lethal point. It can be seen, from the experiments done in the large aquarium, that as the fish behavior changed from no stimulation to excess stimulation the potential had to be increased. There is considerable overlap and divergence. The results--20 volts for Black bullhead and Bluegill, 18 volts for Redear, and 17 volts for Longear, all applied at 2.8 kilohms water resistance--seem to show evidence that these are good potentials at the designated resistance to use for optimum galvanotropism, and that the potential to produce this result does not vary much between species; but the other values are too scattered to use as supporting evidence. However, this series of experiments was done to explore the nature of the four previously named factors, to learn what equipment was effective, and a routine to follow. It was found that a succession of impulses of extremely short duration produced the better reactions. The fish overturned and were stunned but did not travel to the positive pole when sustained potentials were applied. It was because of this behavior that the writer concluded the reaction to be a reflex rather than a tropism. If the latter were the case, the fish should have responded by gathering at the positive pole.

Table 2. Good galvanotropic responses of Fathead minnows to direct current impulses in a 6 by 18 inch aquarium. The data is arranged in a sequence from low to high water resistance with the voltage used, shown for each resistance.

Water Resistance in Kilohms	Logarithm of Resistance	Volts Applied	Milliamperes
0.104	-0.98	13	600
0.128	-0.89	16	800
0.155	-0.81	19	900
0.165	-0.78	20	1000
0.245	-0.61	25	450
0.245	-0.61	24	400
0.37	-0.43	32	900
0.76	-0.12	40	500
0.98	-0.08	41	480
1.0	0.0	40	400
1.0	0.0	41	---
1.0	0.0	43	---
1.0	0.0	46	---
1.5	0.18	42	300
1.87	0.27	46	280
2.0	0.30	20	100
2.0	0.30	39	200
2.0	0.30	41	220
2.55	0.41	45	200
2.9	0.46	48	190
3.0	0.48	27	77
3.0	0.48	17	---
3.0	0.48	45	---
3.0	0.48	48	---
3.0	0.48	23	---
3.0	0.48	47	160
3.2	0.51	17	---
4.0	0.60	24	---
4.0	0.60	35	100
4.0	0.60	33	97
4.0	0.60	47	150
4.2	0.62	47	125
4.6	0.66	39	---
4.7	0.67	47	110
5.0	0.70	52	115
5.0	0.70	26	60
5.0	0.70	47	---
5.0	0.70	53	---

Table 2. (Continued)

Water Resistance in Kilohms	Logarithm of Resistance	Volts Applied	Milliamperes
5.0	0.70	54	---
5.3	0.72	54	120
5.6	0.75	53	---
6.0	0.78	41	65
6.7	0.83	55	100
7.0	0.84	55	---
8.0	0.90	44	50
8.5	0.93	59	80
8.8	0.94	50	59
9.0	0.95	50	---
9.0	0.95	35	53
9.0	0.95	60	75
10.0	1.00	28	---
10.3	1.01	64	65
10.5	1.02	42	44
10.5	1.02	44	---
11.7	1.07	54	46
11.8	1.07	54	---
12.0	1.08	54	---
12.0	1.08	54	---
12.0	1.08	54	---
12.0	1.08	60	---
12.3	1.09	44	35
12.3	1.09	75	60
13.0	1.11	42	---
14.0	1.15	58	43
14.0	1.15	30	23
15.0	1.18	44	---
15.0	1.18	60	40
15.5	1.19	80	62
16.0	1.20	68	---
16.0	1.20	76	45
17.5	1.24	70	40
18.0	1.25	37	16
18.0	1.25	60	---
18.0	1.25	70	---
18.6	1.27	48	---
19.0	1.28	60	30
19.0	1.28	80	---
19.0	1.28	50	---
19.0	1.28	48	---
21.0	1.32	88	---

Table 2. (Continued)

Water Resistance in Kilohms	Logarithm of Resistance	Volts Applied	Milliamperes
21.0	1.32	84	---
21.0	1.32	63	---
23.0	1.36	74	25
24.0	1.38	64	---
25.0	1.40	60	24
25.0	1.40	75	---
25.0	1.40	48	---
26.0	1.41	76	35
27.0	1.43	64	26
28.0	1.45	68	---
29.0	1.46	75	24
34.0	1.53	84	24
35.0	1.54	80	22
36.0	1.54	84	24
39.0	1.59	96	26
47.0	1.67	90	---
48.0	1.68	105	24
48.0	1.68	108	---
50.0	1.70	108	---
50.0	1.70	110	---
64.0	1.81	100	---
65.0	1.81	122	---
70.0	1.84	113	---
87.0	1.94	125	15
89.0	1.95	125	13
94.0	1.97	145	---
108.0	2.03	140	12
114.0	2.06	125	9
118.0	2.07	125	---
120.0	2.08	133	11
120.0	2.08	150	---
122.0	2.08	128	10
142.0	2.15	133	10
150.0	2.18	135	---
150.0	2.18	180	---
165.0	2.22	155	---
165.0	2.22	165	---
210.0	2.32	150	4
220.0	2.34	180	---
230.0	2.36	70	---
230.0	2.36	95	---

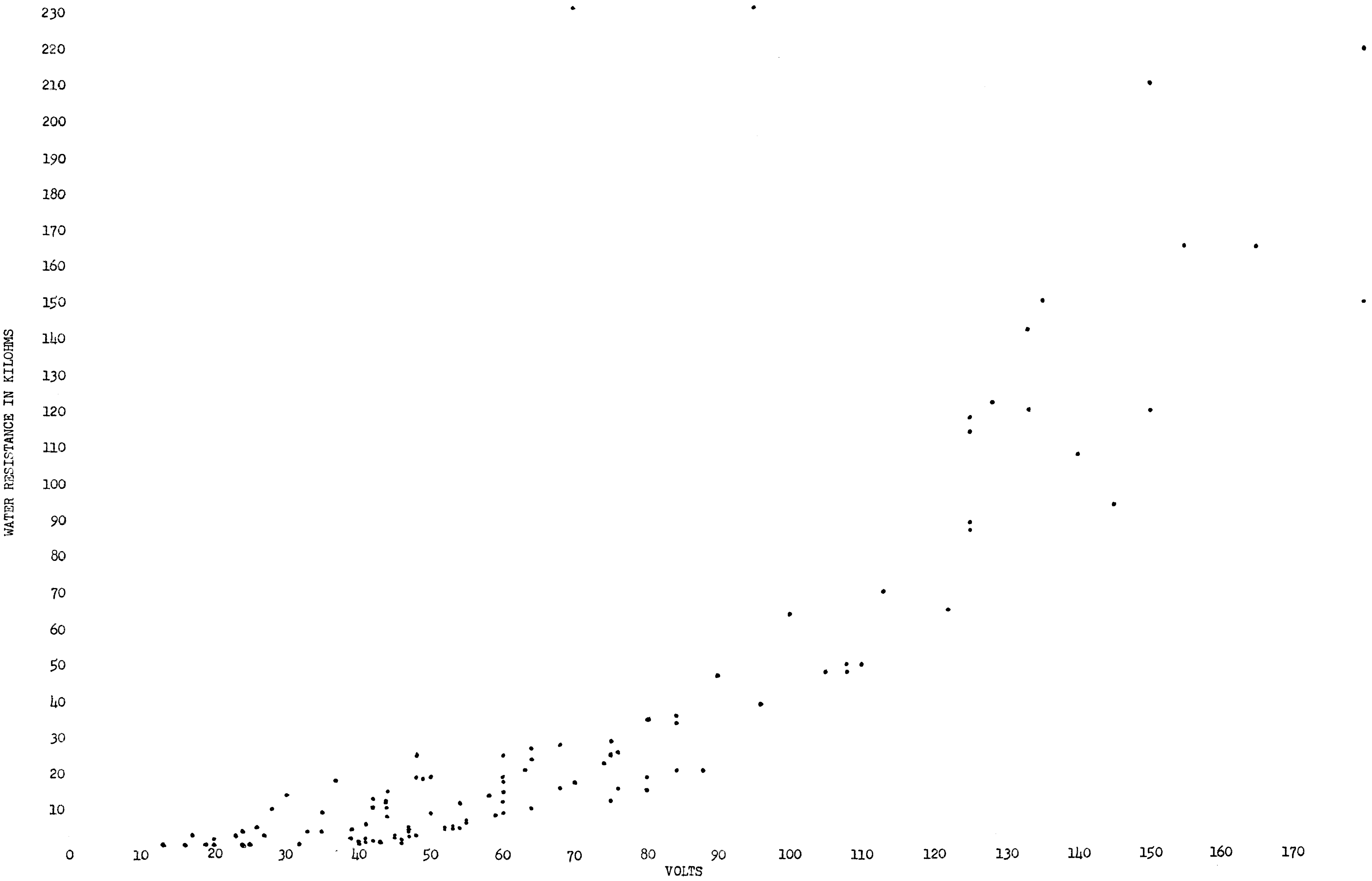

Fig. 1. A graph of the voltages and water resistances
at which good galvanotropism of the minnows was observed

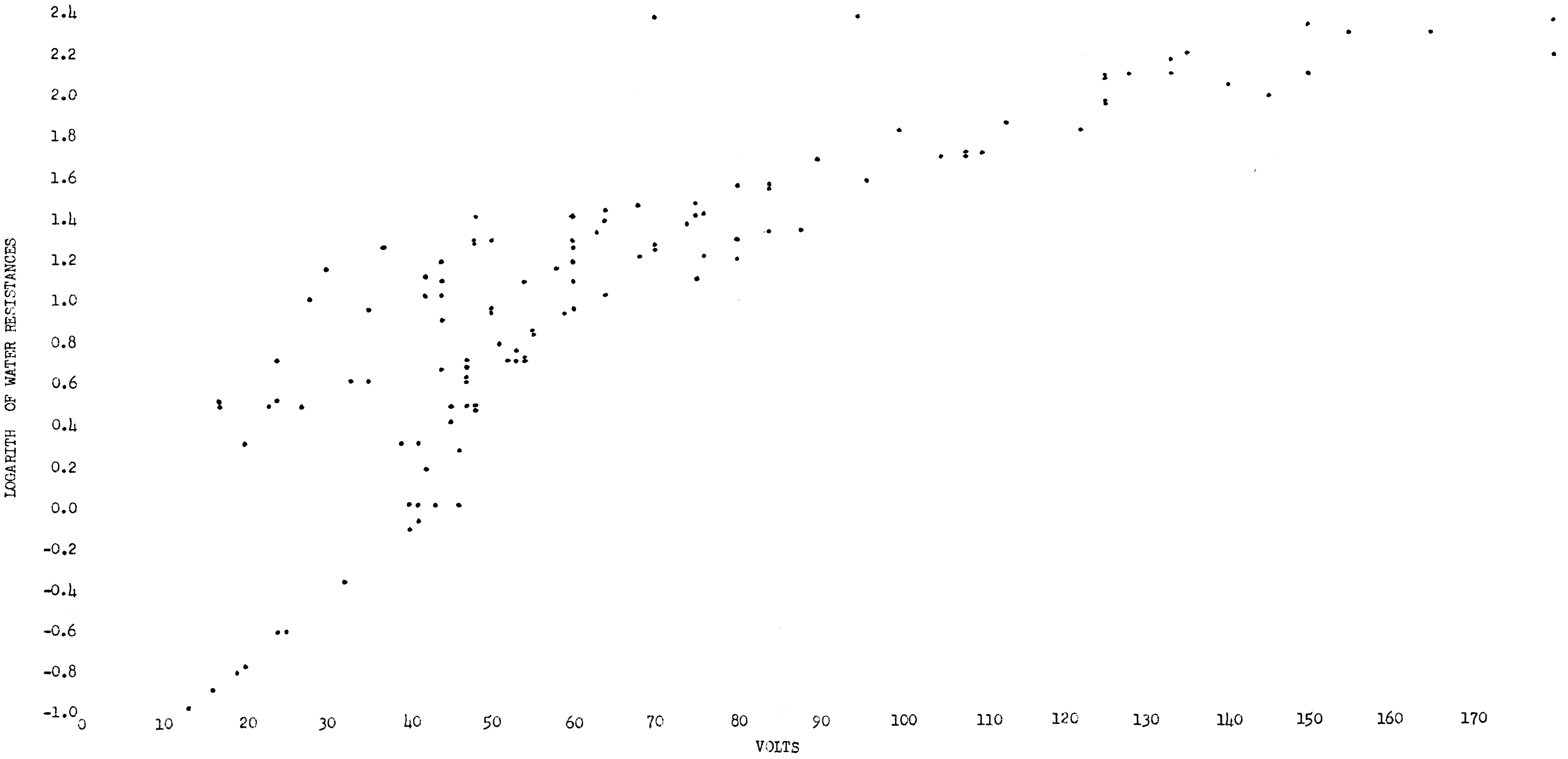

Fig. 2. Volts plotted with logarithm of resistances show the exponential properties of Fig. 1.

The Reactions of Fathead Minnows

Table 2 shows the good galvanotropic responses of Fathead minnows and the water resistances arranged from low to high at which the reactions occurred. The results indicate that the voltage required to produce a galvanotropic response at any one resistance is not critical. On the contrary, a band of potentials of considerable width can be employed without harm to the fish. Figure 1 illustrates a definite need for increased voltage as the resistance of the water increases. The prospect that the graph points might represent an exponential curve led to the plotting of the voltage with the logarithm of resistances (Fig. 2). If this is true, the points should represent a straight line. The graph in part represents an exponential curve, but data which were derived from better controlled conditions are necessary for conclusive evidence.

The data in Table 3 are the results of a series of experiments which illustrate reactions ranging from no galvanotropism to excessive response and within each reaction the data arranged from low to high potentials. All the terms referring to reactions are the same as those explained on page 12, except that minimum galvanotropism is substituted for threshold. Minimum galvanotropism was used to describe a reaction in which the fish when stimulated showed a slight movement toward the positive electrode. Because the crude ohmmeter and larger aquarium were used to obtain the results shown in Table 1, the results should probably not be considered comparable with those of Tables 2 or 3. The relation between increased galvanotropism in minnows and increased potential of the impulses for a given resistance shows a definite trend in spite of the fact that some results overlap and some are inconsistent.

Table 3. Reactions of Fathead minnows to direct current impulses in a 6 by 18 inch aquarium with the water resistance, the voltage used, and the current when measured.

Water Resistance in Kilohms	Volts Applied	Milliamperes	Reactions
18.7	15.0	---	*
25.0	92.0	---	*
222.0	163.0	---	*
0.08	3.0-4.0	220.0-340.0	**
0.175	6.0-9.0	170.0-310.0	**
0.38	7.0-9.0	140.0-180.0	**
27.5	7.0	1.2	**
0.45	8.0	100.0	**
0.76	8.0-9.5	---	**
4.2	8.0	10.0	**
1.26	8.5-9.5	---	**
0.43	9.0	120.0	**
1.65	9.5	---	**
1.7	9.5	32.0	**
2.7	13.0-14.0	26.0-32.0	**
4.1	16.0-20.0	22.0-29.0	**
7.2	17.5	15.0	**
2.0	20.0	100.0	**
18.7	20.0	---	**
24.0	28.0	---	**
15.0	40.0	18.0	**
18.6	44.0	---	**
0.8	21.0	250.0	***
10.5	33.0	---	***
18.7	33.0	---	***
18.7	36.0	---	***
24.0	40.0	---	***
24.0	64.0	---	***
50.0	112.0	---	***
69.0	125.0	18.0	***
0.104	13.0	600.0	****
0.128	16.0	800.0	****
3.0	17.0	---	****
3.2	17.0	---	****
0.155	19.0	900.0	****
0.165	20.0	1000.0	****
2.0	20.0	100.0	****
3.0	23.0	---	****

Table 3. (Continued)

Water Resistance in Kilohms	Volts Applied	Milliamperes	Reactions
0.245	24.0	400.0	****
4.0	24.0	---	****
0.245	25.0	450.0	****
5.0	26.0	60.0	****
3.0	27.0	77.0	****
10.0	28.0	---	****
14.0	30.0	23.0	****
0.37	32.0	900.0	****
4.0	33.0	97.0	****
4.0	35.0	100.0	****
9.0	35.0	53.0	****
18.0	37.0	16.0	****
2.0	39.0	200.0	****
4.6	39.0	---	****
0.76	40.0	500.0	****
1.0	40.0-43.0	400.0	****
0.98	41.0	480.0	****
1.0	41.0	---	****
2.0	41.0	220.0	****
6.0	41.0	65.0	****
1.5	42.0	300.0	****
10.5	42.0	44.0	****
13.0	42.0	---	****
1.0	43.0	---	****
8.0	44.0	50.0	****
10.5	44.0	---	****
12.3	44.0	35.0	****
15.0	44.0	---	****
2.55	45.0	200.0	****
3.0	45.0	---	****
1.0	46.0	---	****
1.87	46.0	280.0	****
3.0	47.0	160.0	****
4.0	47.0	150.0	****
4.2	47.0	125.0	****
4.7	47.0	110.0	****
5.0	47.0	---	****
2.9	48.0	190.0	****
3.0	48.0	---	****
18.6	48.0	---	****

Table 3. (Continued)

Water Resistance in Kilohms	Volts Applied	Milliamperes	Reactions
19.0	48.0	---	****
25.0	48.0	---	****
8.8	50.0	59.0	****
9.0	50.0	---	****
19.0	50.0	---	****
5.0	52.0	115.0	****
5.0	53.0	---	****
5.6	53.0	---	****
5.0	54.0	---	****
5.3	54.0	---	****
11.7	54.0	46.0	****
11.8	54.0	---	****
12.0	54.0	---	****
12.0	54.0	---	****
12.0	54.0	---	****
6.7	55.0	100.0	****
7.0	55.0	---	****
14.0	58.0	43.0	****
8.5	59.0	80.0	****
9.0	60.0	75.0	****
12.0	60.0	---	****
15.0	60.0	40.0	****
18.0	60.0	---	****
19.0	60.0	30.0	****
25.0	60.0	24.0	****
21.0	63.0	---	****
10.3	64.0	65.0	****
24.0	64.0	---	****
27.0	64.0	26.0	****
16.0	68.0	---	****
28.0	68.0	---	****
15.3	70.0	50.0	****
17.5	70.0	40.0	****
18.0	70.0	---	****
230.0	70.0	---	****
23.0	74.0	25.0	****
12.3	75.0	60.0	****
25.0	75.0	---	****
29.0	75.0	24.0	****
16.0	76.0	45.0	****

Table 3. (Continued)

Water Resistance in Kilohms	Volts Applied	Milliamperes	Reactions
26.0	76.0	35.0	****
15.5	80.0	62.0	****
16.0	80.0	---	****
19.0	80.0	---	****
35.0	80.0	22.0	****
21.0	84.0	---	****
34.0	84.0	24.0	****
36.0	84.0	24.0	****
21.0	88.0	---	****
47.0	90.0	---	****
230.0	95.0	---	****
39.0	96.0	26.0	****
64.0	100.0	---	****
48.0	105.0	24.0	****
48.0	108.0	---	****
50.0	108.0	---	****
50.0	110.0	---	****
70.0	113.0	---	****
65.0	122.0	---	****
87.0	125.0	15.0	****
89.0	125.0	13.0	****
114.0	125.0	9.0	****
118.0	125.0	---	****
122.0	128.0	10.4	****
120.0	133.0	11.0	****
142.0	133.0	10.0	****
150.0	135.0	---	****
108.0	140.0	12.0	****
94.0	145.0	---	****
120.0	150.0	---	****
210.0	150.0	4.0	****
165.0	155.0	---	****
165.0	165.0	---	****
150.0	180.0	---	****
220.0	180.0	---	****
217.0	183.0	---	****
10.5	48.0	---	*****
16.4	80.0	---	*****
33.5	90.0	---	*****
21.4	98.0	---	*****

Table 3. (Continued)

Water Resistance in Kilohms	Volts Applied	Milliamperes	Reactions
73.0	120.0	---	*****
90.0	150.0	---	*****
90.0	163.0	---	*****
165.0	195.0	---	*****

*	No reaction evident in fish.
**	Minimum galvanotropic response.
***	Weak galvanotropic response.
****	Good galvanotropic response.
*****	No galvanotropic response, fish were caused to dart first one direction and then another, or were stunned.

An explanation of these inconsistencies is purely speculation. One might observe the fish moving toward the positive electrode at the time an impulse was applied and infer that the movement was a response and not coincidence. Such an inference could most easily be made when charting threshold or minimum galvanotropisms, the differences in the character of the impulse (wave form and duration), the frequency of the applied stimulus, the condition of the fish, the individual differences of fish, the developments of a conditioned reflex, and the fish size, are some of the variables that might explain the inconsistencies. The latter two factors were minimized by use of a different fish in each trial, and those used restricted to minnows that were two to four centimeters long. When adult minnows (5-6 centimeters long) were included with the smaller ones, the larger fish responded more readily. When higher resistances were used, galvanotaxis was not evidenced but the fish were stunned. Although water temperature records are not included because no temperatures below 22° Centigrade were used, it appeared that the fish were more responsive at the lower temperatures for all potentials used at a given resistance.

The field experiments were unsuccessful. The fuse was blown on the first trial although the electrodes were forty feet apart. Measurement of the resistance between the electrodes revealed 100 ohms or only one-thirtieth of that required for the 1000 volt, 1/3 ampere output of the dynamotor. Moving the electrodes farther apart did not increase the resistance. When the wire was disengaged from the positive electrode and buried in the moist ground at the shore of the pond, the correct resistance was reached, but the use of the ground as an electrode defeated the purpose sought. Further work in this experiment would necessitate a device which would store enough electrons and release them quickly as an impulse in order to convert the 1/3 ampere to the needed current at the available potential, or a new source of electrical supply that would have sufficient power to fulfill the requirements. Due to lack of time, work on this phase of the experiment was not continued.

Besides galvanotropic responses, other interesting observations were made. When the electrodes were placed in their respective ends of the aquarium, and the telegraph key tapped, a slight deflection of the panel ammeter was noted before the power supply was connected. This showed that the unit consisting of the aquarium and its electrodes was acting as a very low voltage battery. The current and voltage measured by a sensitive meter was shown to be 0.8 milliampere and 21 millivolts respectively in the two-foot aquarium. While experimenting with the minnows in the eighteen-inch aquarium, a leech was accidentally dropped in the water and an electrical impulse applied. The leech reacted actively but was attracted to the negative electrode while the fish were attracted to the positive. Several trials were made with this leech, and invariably he went to the negative electrode. Kudo (1950) in his description of experiments on electrical effects of protozoa mentions that certain species would go to the positive while other species would go to the negative electrode.

It was hoped that a formula for the construction of a large electrical seine could be derived from data obtained by the use of small aquaria with the water resistance, potential, water volume, and kind of fish controlled. The information attained in the study was not so profound and inclusive as had been hoped. Some progress has been made regarding the nature of the reactions of fish to direct current impulses and the effect of water resistance on the potentials needed.

The need for an increase of voltage as the water resistance increased would be a factor to consider in the design of an electric seine. The fact that a range of potentials is effective for each water resistance would decrease the complexity of the apparatus needed. However, it seems that no one band of potentials will effectively collect fish of all sizes and kinds. If the reaction of a fish to direct current is a reflex and not a tropism, the need for an impulse instead of a constant current flow is evident.

The writer would like to repeat and expand the study with increased facilities, such as, a wide range resistance bridge and unlimited power with proper regulation. Added to the power supply should be a device that would release the measured and controlled impulses at exact moments and at desired intervals. A means of measuring the current flow at any location in the water between the electrodes seems necessary to properly understand the characteristics of current flow in the water.

The problems to be considered in the construction of an effective direct current seine do not seem impossible but appear to be more involved than was anticipated when this study was begun.

V. SUMMARY

1. The effect of water resistance on the voltage required to produce galvanotropism in fish was studied.
2. The reactions of certain fish to an impulse of direct current electricity are presented.
3. A band of potentials that caused galvanotropism was found to exist with each water resistance used, and the band was found to be composed of potentials of higher voltages as the resistance was increased.
4. The immediate stimulus produced in a fish by a suddenly applied impulse indicates that the reaction is a reflex.
5. Currents applied to equal volumes of water between the electrodes were observed to increase as the effective potentials and water resistances decreased.
6. The logarithm of the water resistances plotted with the effective potentials produced a graph that resembled an exponential curve.
7. Some suggestion for future studies leading to information necessary for the construction of an electric seine are presented.

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VITA

Pierre Chester Lawson
candidate for the degree of
Master of Science

Thesis: REACTIONS OF FISH TO VARIOUS INTENSITIES OF DIRECT CURRENT ELECTRICITY IN WATERS WITH DIFFERENT CONDUCTIVITY

Major: Zoology

Biographical and Other Items:
Born: March 22, 1920 at Omaha, Nebraska
Undergraduate Study: University of Omaha Education, 1940-1945
Graduate Study: O.A.M.C., 1949-1952
Experiences: Navy, 1945-1949

Member of Wildlife Society

Date of Final Examination: February 3, 1953

THESIS TITLE: REACTIONS OF FISH TO VARIOUS INTENSITIES OF DIRECT CURRENT ELECTRICITY IN WATERS WITH DIFFERENT CONDUCTIVITY.

AUTHOR: PIERRE CHESTER LAWSON

THESIS ADVISER: WILLIAM H. IRWIN

TYPIST: CHRISTINE M. HANCOCK