FACTORS INFLUENCING THE ATTRACTION OF ATLANTIC HERRING, *CLUPEA HARENGUS HARENGUS*, TO ARTIFICIAL LIGHTS

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ABSTRACT

Using artificial lights to attract fish at night is a common and often effective fishing technique. With Atlantic herring the attraction is somewhat uncertain, however, and does not always take place. This paper describes experiments which showed that, in addition to the inherent variability of the fish themselves, certain external conditions can modify the attraction to the light. Attraction was greater at low than at high temperatures, greater with underwater lights than with lights above the surface, and greater when the fish were previously adapted to light than when they were adapted to darkness. Very bright light (illumination 20–600 lux), especially above the surface, tended to repel the fish. Light of intermediate intensity (illumination 1–30 lux) was most effective.

The behavioral responses comprised an initial attraction resembling positive phototaxis, followed by apparent disorientation, or confusion. The disorientation may have been due to attempts by the fish to respond with a dorsal light reaction, i.e. to assume postures which would orient their dorsal surface toward the light source even when such postures interfered with normal swimming.

The use of artificial lights for attracting fish is a common practice in fisheries throughout the world. The methods have changed but little, however, the chief improvement being the substitution of electric light sources for open flames or fuel-burning lamps.

The attraction of Atlantic herring (*Clupea harengus harengus*) with lights has been studied experimentally and adapted to some extent for commercial fishing. Lights have been used routinely on Norwegian purse seiners for many years to attract herring. According to Dragesund (1958), herring are not always attracted to lights, however, and even the fishermen do not agree about the behavior of herring in response to the lights used on seiners. Dragesund studied the behavior of fish schools from a research vessel and distinguished the following kinds of reaction to the attracting light:

1. Fish descend and pack together.
2. Fish disperse.
3. Fish rise toward light, then shortly descend.
4. Fish pack together, then rise toward the light.

Blaxter and Parrish (1958) were able to attract young herring (5–25 cm.) to underwater lights at several levels of brightness and to bring them to the surface by raising the lights. Tibbo (1965) reported that herring in a large tank were attracted to artificial lights of various intensities and colors, although they were repelled at the highest intensities. Gauthier (in press), collaborating with fishermen on a commercial purse seiner, reported catches of herring of 25 to 40 tons in trials with underwater lights in the Gulf of St. Lawrence.

Lights were used traditionally along the Atlantic Coast of North America for catching juvenile herring by "torching," a method probably adopted from the Indians. A kerosene- or gasoline-burning flare, or even a more primitive torch of combustible material on a stick, was mounted on the bow of a small boat. The procedure has been described by Earll (1887) as follows. "The fishermen usually go to the shore late in the afternoon and time their departure so as to reach the fishing grounds shortly after sunset. As soon as it becomes sufficiently dark, the fire is lighted, one man takes his position in the stern to steer the boat and another stations himself in the bow, armed with a dip-net for securing the fish as they gather in little bunches just in front of the light. The remaining members of the crew row the boat rapidly through the water, while the man in the bow is busily engaged in throwing the fish into the boat

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by means of his dip-net. Great numbers of herring are attracted by the light and it is not uncommon for fifteen or twenty barrels to be taken in a few hours."

The variability of the herring's response to light is a characteristic feature and has been noted by many investigators. Blaxter and Holliday (1963) stated ". . . . Such reactions will vary widely depending on the environment and the physiological state and age of the fish as well as on the type of stimulus itself." Other authors have demonstrated how many factors, external and internal, can vary the response of herring and other species to artificial lights. Kurc (in press) and others have pointed out how the thermocline may prevent fish from rising to a light, or may hold them in the surface water so that they can be more readily attracted. Strong ambient light (e.g. moonlight) may reduce the effectiveness of the attracting light (Kurc, in press; Ström, in press). Woodhead (1956) showed that starvation reversed the normal negative phototaxis of the minnow *Phoxinus*. Andrews (1946) found that the attraction to light of the white sucker (*Catastomus*) decreased with increasing temperature. Sudden changes in illumination may cause the fish to disperse instead of attracting them (Ström, in press; Gauthier, in press).

Although routine, uncritical use of lights to attract fish may sometimes be successful, far greater effectiveness might be achieved by a better understanding of the underlying behavior of the fish and its response to lights. Moreover, lights might be of definite value in some circumstances where they are not now used. In Maine the use of lights for catching herring is generally illegal because many fishermen believe that the lights tend to disperse the herring rather than attract them (Scattergood and Tibbo, 1959). This restriction appears to be an instance where profitable use of lights has been discouraged because the underlying behavior of the fish has been inadequately understood.

This paper is an attempt to explain some of the biological and other factors that are conducive to the attraction of herring by light.

METHODS

The fish used in the experiments were immature Atlantic herring of age groups O (brit), I, and II, which are processed as Maine sardines. They were 75 to 200 mm. in total length and were taken from commercial catches near Boothbay Harbor, Maine. The fish were held under the prevailing seasonal conditions of salinity, temperature, and dissolved oxygen in large tanks provided with running sea water and were fed daily a mixture of ground trout food and canned cat food.

The experiments were conducted in a separate tank. This tank was fiberglass, 5.5 m. long, 0.4 m. deep, and 0.3 m. wide. An incandescent lamp suspended in a glass cylinder at each end of the tank provided the attracting illumination; by raising or lowering the lamp bulb in the cylinder, the light source could be located above or below the surface. Sea water entered the left-hand end of the tank and drained off at the right. A slight drift (less than 4 cm. per minute) toward the right resulted. This and other sources of left-right bias were compensated by periodically alternating the location of the light source between the right and left ends of the tank with a double throw switch. For temperatures above the seasonal sea-water temperature, the incoming water was heated. An air bubbler near the point of entrance and another near the center of the tank provided sufficient mixing so that temperature differences within the tank did not exceed 1° C. Cooling pipes, carrying a chilled ethylene glycol-water mixture, located along the walls of the tank provided uniform refrigeration when below-seasonal temperatures were required.

Variations in dissolved oxygen were achieved by recirculating the water through a tank of pure oxygen under pressure (1.5–2.0 atmospheres) or through a vacuum. These devices provided a range of 50 percent to 250 percent oxygen saturation in the experimental tank.

The intensity of the attracting lights was varied by using light bulbs of different wattages or by varying the supply voltage. The light gradient for each intensity and source position (fig. 1) was measured with a photovoltaic light meter having a waterproof housing for the sensitive element. This element was held in a plane normal to the direction of the light rays in the water. The meter was factory-calibrated for a spectral response corresponding to that of the human eye. This response is not identical to that given for herring (Blaxter, 1964), but is very similar; the difference was so small that special calibration of the instrument did not seem warranted.

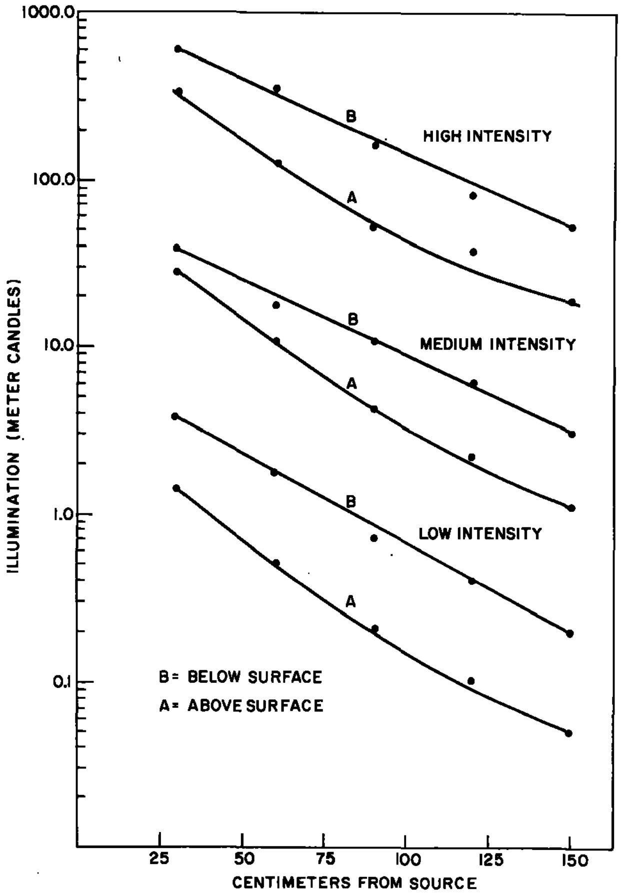

FIGURE 1.—Light gradients at the three light intensities used in the experiments.

The fish were taken at random from a storage tank and transferred to the experimental tank, where they were allowed to accommodate for periods of 30 minutes to 15 hours before each trial. Except where light or dark adaptation was at issue in the experiment, the period preceding each trial was at room illumination. I found no significant difference in the responses of individual herring allowed a half-hour or full-hour period of accommodation to the tank. Once the fish recover from the initial disturbance after transfer, it is not likely that any further time for accommodation is necessary. This factor should not affect the results of the experiments, because for any given experiment the accommodation periods of all fish were the same. Accommodation periods were progressively reduced throughout the series to save time.

No attempt was made to acclimatize the fish to arbitrarily selected temperatures because facilities for this purpose were not available. The fish were transferred from water at seasonal temperatures to the experimental tank. Because temperature acclimatization exerts a definite influence on the subsequent reactions of fish to temperature, it could conceivably affect their response to light at different temperatures. For that reason I have specified the acclimatization (=seasonal) temperature for the fish used in each experiment (table 1). It will be noticed, however, that several combinations of acclimatization and experimental temperatures produced no qualitative difference in the results of experiments where the effect of temperature was being tested.

TABLE 1.—*Summary of pretrial experience of experimental herring*

Experiment number	Accommodation period	Acclimatization temperature	Experimental temperature	
	Hours	° *C.*	° *C.*	*Month*
1	15	5	6, 12, 16	December
2	15	3	5	February
3	1–2	10–13	15–17	October
4	½–2	10–13	15–17	October
5	½–2	10	15–17	October
6	6	5	6, 12, 16	December
7	6	10–14	5–6, 15–17	July
8	3	13–16	8–10, 15–17	July–August
9	5	2–3	4–6	March
10	6	10–14	15.5–17	June
11	6	10–14	6–9	July
12	6	13–16	15–17.5	August–September
13	1	13	15–17	October
14	3	3	5	January
15	6	13–16	15–17.5	August–September
16	1	14–16	15.5–17	September

An experiment consisted of several trials in which the variables of interest were given predetermined values; each trial could be given a different set of conditions or could replicate another trial. For experimental variables that could be changed quickly (e.g. light location or intensity), several trials were completed in a single day. For conditions that required a longer time to establish (e.g. temperature or gas content), only one trial could be completed in a day, and an experiment might last several weeks. In protracted experiments of this sort, when only two treatments were involved, the trials were alternated; when several were involved in the same experiment, the trials were ordered randomly.

Two routine procedures were used. When fish were tested singly (experiments 1 to 4), the attracting light was turned on at the right end of the tank for 5 minutes, and the amount of time spent by the fish in the illuminated half of the tank recorded. Then the illumination was switched to the left end of the tank and the time spent in that half by the fish was recorded. The illuminated half of the tank was reversed end for end every 5 minutes over 30-minute periods. The score by which the attraction to light was measured was the cumulative amount of time spent by the fish in the illuminated half of the tank.

The second routine procedure was used whenever a group of fish were tested (experiments 5 to 16). Ten randomly selected herring were placed in the tank, the attracting light on the right was turned on, and the number of fish present in the illuminated half was counted each minute for 5 minutes. The illumination was then switched to the left side, and the fish present in the illuminated half of the tank were again counted each minute for 5 minutes. The lights were, thus, alternated from end to end at 5-minute intervals until 30 counts had been made. The sum of the 30 counts was the score for groups of fish. A variant of this procedure was used in two experiments (13 and 16). Each trial lasted only 1 minute, and counts were made at 15, 30, 45, and 60 seconds. The light position remained the same throughout the period of one trial, but equal numbers of trials were made with the left side illuminated and with the right side illuminated.

In no experiment were the same fish used in successive trials; after being used once, every fish was returned to a separate holding tank and was not used again for at least 2 weeks.

Comparisons of scores between only two conditions were analyzed statistically with a "t"-test; comparisons among several kinds and levels of treatment were analyzed with a fixed-model analysis of variance.

GENERAL BEHAVIOR

After the fish had become accustomed to the experimental tank their behavior stabilized into one of three general patterns: (1) swimming regularly back and forth from one end of the tank to the other (in a loose school, if in a group), (2) remaining at one end of the tank, or (3) milling about randomly throughout the tank. After the room was darkened and the attracting light was turned on, whatever behavior pattern had been adopted by that particular fish or group of fish continued; this behavior tended to obscure the response of the herring to the attracting light. Although a brief flurry of activity near the lamp frequently occurred at the begining of each trial, the degree of attraction was not obvious by casual observation; it could be demonstrated only by repeated counts over an extended period. The fish showed no tendency to gather in any locality of optimum light intensity.

The exact behavioral mechanisms involved in the attraction of fish to artificial lights are not known, although several theories have been proposed, ranging from a straightforward positive phototaxis to a conditioned response where light is associated with food. One of the more interesting theories is that of Verheijen (1959 and in press). He suggested that an artificial light creates an unnatural light field which leads to a disoriented behavior of the fish, because "such simplified visual environments" may not "deliver adequate information to all integration levels involved in the performance of the fish's natural behavior." The net effect is one of trapping fish rather than merely attracting them.

Close observation of herring in some of my own experiments yielded clues about their behavior in an unnatural light field which may amplify somewhat the ideas of Verheijen. The typical behavior of a single herring consisted of the following events:

(1) Starting from the dark half of the tank, the fish swims slowly at first, then with increasing speed directly toward the light.
(2) Upon reaching the light, sometimes striking it squarely with its snout, the fish turns more or less broadside to it and proceeds to circle it, or swim to and fro in short courses which lie generally along the circumference of a circle around it.
(3) This behavior is frequently interrupted by movements which give the impression of confusion or disorientation. Close observation indicates that these movements are, in fact, attempts by the fish to orient its dorsal surface toward the light source. When the light is under water, these attempts lead the fish to assume momentarily vertical postures or horizontal postures on its side with its back toward the light.

(4) In retreating from the light, the fish swims in a zigzag course, the legs of which become progressively more nearly perpendicular to the direction of the light, and the fish eventually returns to it; or the legs become progressively more oblique and the fish escapes into the darkened zone.
(5) After a short stay in the dark zone, the fish repeats the entire procedure.

Many of these actions appear to be manifestations of the "dorsal light reaction" (Frankel and Gunn, 1961) in which a fish orients itself in a position so that its dorsal surface is more or less perpendicular to the direction of the light rays. Woodhead and Woodhead (1955) have described such a phenomenon in herring larvae. Under natural lighting, where the predominant direction of the light is downward, the herring can orient to the rays in its normal swimming posture, descending when the light is too strong, and rising when it decreases. When a single light source is close to the surface or beneath it, phototaxis can take place with no departure from the normal swimming posture, but dorsal orientation to the light (except when the fish is directly beneath it) requires postures that interfere with normal swimming—hence, the apparent disorientation and difficulty in escaping the influence of the light.

VARIATION IN SUSCEPTIBILITY TO LIGHT ATTRACTION

Whatever may be the effect of external conditions in modifying the response of herring to light, individual differences among the fish lead to wide variation in this response even under identical external conditions. This variability is illustrated by five experiments.

FREQUENCY DISTRIBUTION OF THE RESPONSE TO LIGHT OF INDIVIDUAL FISH

Individual fish vary in behavior as well as physical characteristics. If this variation were reasonably close to a normal distribution, the statistical treatment used in this study would be more likely to be valid than if the variation was not normally distributed. The following experiment was made to examine the variation among individual fish.

Experiment 1. Ninety herring, selected at random, were observed individually to determine the degree to which they were attracted to an underwater light of medium intensity; 30 were observed at 6° C., 30 at 12° C., and 30 at 16° C. Scoring was based on the amount of time spent in the illuminated half of the tank. The mean scores of 16.2, 17.2, and 17.8 at 6°, 12°, and 16° C., respectively, were not significantly different ($F=0.92$, $P>0.1$). The three frequency distributions each showed a reasonable tendency toward normality (fig. 2). When all the scores were combined, this tendency was more pronounced (fig. 2, dashed line).

CHANGES IN SUSCEPTIBILITY TO LIGHT ATTRACTION

If herring differ from individual to individual in their susceptibility to light attraction, do individuals vary in themselves over a period of time?

Experiment 2. To answer this question, 25 herring were fin clipped to identify individuals and tested and scored as in the preceding experiment.

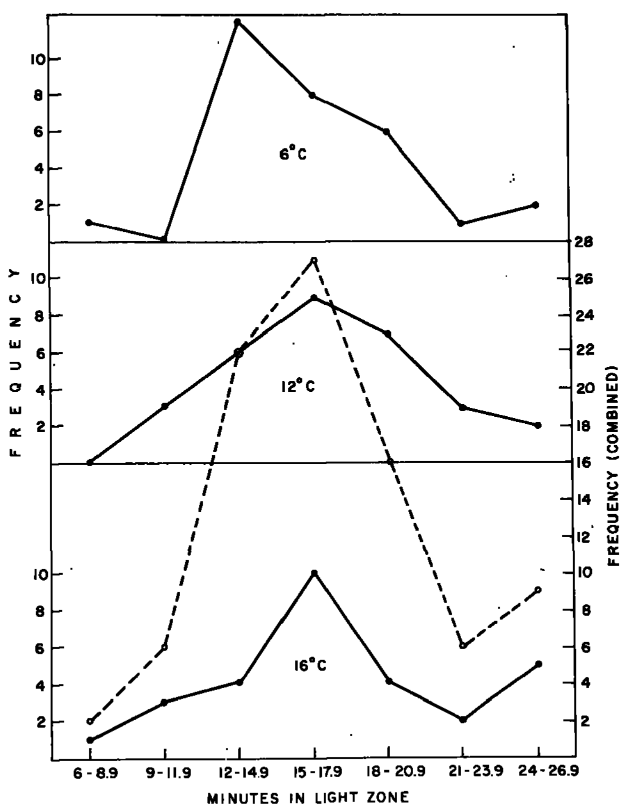

FIGURE 2.—Frequency distribution of scores (experiment 1) based on the time in minutes out of a possible 30 minutes spent by individual herring in the illuminated half of a tank. Solid lines, distribution of scores at each of three temperatures; dashed line, distribution of all scores, regardless of temperature.

They were then transferred to another tank and left undisturbed for 1 week. After this interval they were again scored as before. (Two of these fish died in the interval, so that data from only 23 were complete.)

If the degree of response is a fixed characteristic, the response should be the same on the second occasion as on the first, or if a change has occurred, it should affect all the fish more or less similarly, so that a high degree of correlation should be found between the scores in the first test and the scores in the second. Actually, some fish increased their scores and some decreased them (table 2); some changed from a positive response (more than half the time spent in the lighted zone) to a negative one. The correlation coefficient of $R=0.55$ was very weak, although it was barely significant. This result can be interpreted to mean that although individuals tend to maintain a certain inherent response characteristic, this characteristic may vary substantially with time.

TABLE 2.—*Scores (number of minutes spent in illuminated half of tank), for individual herring in two 30-minute tests, 1 week apart (experiment 2)*

First score (by rank)	Score 1 week later
Minutes	*Minutes*
25.27	16.18
24.17	19.05
23.18	16.45
21.90	19.32
21.02	19.35
20.57	20.58
20.03	14.15
19.03	18.08
18.98	10.70
18.62	15.43
18.13	14.53
18.08	14.80
17.77	19.37
17.73	18.05
15.83	16.78
15.50	17.98
14.82	20.85
14.17	8.45
14.08	13.88
13.05	9.97
12.48	7.35
12.12	13.20
12.08	11.03

EFFECT OF CONDITION ON SUSCEPTIBILITY TO LIGHT ATTRACTION

There may be many possible reasons for the variability in response among individual fish. Three reasons which readily suggest themselves are differences in sex, physical condition, and age. I did not attempt to determine the effect of sex experimentally because of the need for economy in use of specimens; determination of sex requires killing the fish. Evidence that strong sex differences occur, however, does not show in the frequency distribution of responses. If males and females differed greatly in response, one would expect some indication of bimodality to the distribution.

Experiment 3. To determine the effect of condition, 32 herring were tested individually at 15 to 17° C., and the time spent in the illuminated zone was recorded for each 30-minute trial. The medium-brilliance, subsurface illumination was reversed end for end every 5 minutes according to the routine procedure. Half of the herring were in excellent physical condition and half were starved and emaciated. The mean scores of 18.1 for the fish in good condition and 18.9 for those in poor condition were not significantly different ($F=0.22$).

EFFECT OF AGE ON SUSCEPTIBILITY TO LIGHT ATTRACTION

Two experiments were done to determine whether any differences in attraction to light could be attributed to the age of the herring; the first of these dealt with individual fish, the second with groups of fish.

Experiment 4. Nineteen herring in age group O and an equal number in age group I were tested individually according to the same procedure used in experiment 3. The mean scores of 20.4 for the O-group fish and 19.5 for the I-group fish were not significantly different ($t = 0.59$).

Experiment 5. Herring of age group O and age group I were tested in groups of 10 individuals according to the second routine procedure described under "Methods." The scores were based on the number of fish counted each minute for 30 minutes in the illuminated half of the tank, which was reversed end for end every 5 minutes. The mean scores for 10 trials with each age group were 120 for the O-group and 132 for the I-group fish; the difference was not significant ($F<1.0$).

EFFECTS OF EXTERNAL VARIABLES ON THE ATTRACTION OF HERRING TO LIGHT

EFFECT OF TEMPERATURE

The experiments in the preceding section dealt primarily with variables inherent in the fish themselves. In this and following sections the experiments deal chiefly with external variables. Evidence from experiment 1 indicated that temperature had little effect on the attraction to light of individual fish. The experiments in the present section involve groups of fish and, as will be seen, temperature does exert a definite effect on herring in groups.

Experiment 6 (cf. experiment 1). Ninety herring, selected at random, were tested in groups of 10 individuals at three temperatures: 6°, 12°, and 16° C. Three trials were made at each temperature. The scores of 205, 129, and 121 at the three temperatures, respectively, were significantly different ($F=6.19$, $P<0.05$).

Experiment 7. The purpose and methods of this experiment were similar to those in experiment 6, except that only two temperature levels were provided and these on alternate days. In the previous experiment, trials at low temperature were made first, followed by trials at the two higher temperatures.

Five trials were made at temperatures of 5 to 6° C. and five at 15 to 17° C. The fish were taken from storage at 10 to 14° C. and held 6 hours at the experimental temperature before each trial. The mean scores were 201 at low temperature and 129 at high temperature (table 3). If the scores are treated simply as two sets of five observations, the difference in means is of marginal significance ($t=2.04$, $P=0.075$); if the scores are treated as five sets of paired observations, however, $t=10.1$ and the differences are highly significant. Because the low-temperature score for each trial was consistently higher than the immediately following high-temperature score, the analysis as paired observations seems reasonable, and the hypothesis that lower temperature increases the attraction to light is confirmed.

TABLE 3.—*Comparison of scores*[1] *for light attraction of herring at low and high temperatures (experiment 7)*

	Temp.	Score	Temp.	Score
	° *C.*		° *C.*	
	5.2	180	15.4	120
	5.7	234	16.5	155
	5.5	198	15.2	139
	5.5	179	16.2	115
	5.7	214	16.2	119
Means	5.5	201	15.9	129

[1] Score=sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score=300.

EFFECTS OF TEMPERATURE, LIGHT INTENSITY, AND LIGHT POSITION

Experiment 8. The responses of groups of 10 herring were observed at two temperature levels (8–10° and 15–17° C.), at three levels of light intensity (fig. 1), and with the attracting light either above or below the surface. Each combination of conditions was replicated once. The fish were taken from storage at 13 to 16° C. and held 3 hours at the experimental temperature before each trial. Table 4 shows the scores. The differences in response were highly significant between high and low temperature ($F=69.2$) and between above- and below-surface lights ($F=48.7$). There was also a significant interaction between light position and intensity, such that the bright light above the surface had the poorest attraction and the bright and medium lights below the surface had the greatest. The difference in response due to position of the light was significantly greater at low temperature. In general, below-surface lights were more effective at low temperature than at high.

ATTENUATION OF LIGHT ATTRACTION WITH TIME

Experiment 9. The degree to which light will hold the herring in its vicinity is a significant component of the total attraction to light. This experiment was intended to determine whether this holding effect would decrease with time, and, if so, whether such decrease was affected by light intensity or position.

TABLE 4.—*Comparison of scores*[1] *for light attraction of herring in relation to light location, light intensity, and temperature (experiment 8)*

Light intensity	High temperature (15–17° C.)		Low temperature (8–10° C.)		Mean score
	Light above surface	Light below surface	Light above surface	Light below surface	
High	135	254	122	166	146
	100	254	159	139	
Medium	192	230	159	179	167
	163	229	150	180	
Low	186	212	149	172	159
	180	217	151	164	
Mean score	159	232	148	167	

[1] Score=sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score=300.

The experiment comprised 24 trials. Each trial consisted of three phases: the first, a 30-minute series of counts on a group of 10 fish, the same as the routine procedure used in other experiments; the second, an 18-hour interval with the attracting light left on; and the third, another 30-minute series of counts like the first. The 24 trials repre-

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sented three levels of light intensity (high, medium, and low) and two light positions (above and below the surface). Each combination of lighting characteristics was replicated four times—two with the light on the left during the 18-hour interim and two with the light on the right. Table 5 gives the scores of the trials, before and after the 18-hour interim. The number of fish in the lighted zone was reduced significantly after 18 hours ($F=13.4$, $P<0.01$). This reduction was significantly greater when the lights were above the surface ($F=11.83$, $P<0.01$) than when the lights were below, but the differences in reduction associated with light intensity were not significant.

TABLE 5.—*Comparison of scores*[1] *for light attraction before and after an 18-hour interval of constant stimulus, in relation to light location and intensity (experiment 9)*

Light intensity	Before interval: Light above surface	Before interval: Light below surface	Before interval: Mean	After interval: Light above surface	After interval: Light below surface	After interval: Mean
High	109	138	134	94	130	109
	144	132		80	125	
	109	133		57	114	
	158	149		126	147	
Medium	127	209	154	80	230	133
	177	138		101	149	
	119	188		76	186	
	103	172		87	157	
Low	143	136	151	97	90	117
	224	139		136	90	
	163	133		136	143	
	147	127		138	114	
Mean	143	149		101	139	

[1] Score = sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score = 300.

EFFECT OF OXYGEN CONCENTRATION

The possible importance of oxygen concentration to the light response was suggested partly by observations that the habitat of juvenile herring was frequently supersaturated with oxygen in summer (Colton, Marak, Nickerson, and Stoddard, 1968; Stickney, 1968) and partly by a comment of Kalle (1965) that the vertical migration of herring (usually considered a response to light) might be due to depletion of oxygen in dense schools near the bottom.

Experiment 10. Groups of 10 herring were tested on alternate days in water normally saturated or highly supersaturated with oxygen before each trial. The temperature of the experiment was 15.5 to 17° C.; the mean oxygen levels were 8.1 p.p.m. (98 percent saturation) and 17.2 p.p.m. (212 percent saturation). The herring were taken from storage at 11 to 14° C., 110 to 125 percent O_2 saturation. Each trial consisted of the routine exposure to an attracting light; scores were based on the number of fish counted each minute for 30 minutes in the lighted end of the tank. The mean score for six trials in normal water was 122; that for six trials in supersaturated water was 164. The difference had a "t" value of 2.04 ($P<0.1$); treated as paired data, the differences between each pair of trial scores had a "t" value of 4.28 ($P<0.01$). The experiment seemed to indicate that supersaturation had a significant effect on the attraction of the herring to light. Subsequent experiments (11 to 13) did not corroborate these results, however.

Experiment 11. Herring were taken from holding tanks at 10 to 14° C. and 105 to 130 percent saturation of oxygen and held 6 hours under the experimental conditions before each trial. Normally saturated and supersaturated water averaging 9.6 p.p.m. (93 percent saturation) and 19.7 p.p.m. (185 percent saturation) of oxygen, respectively, at 6 to 9° C. were provided on alternate days. In five trials at each oxygen level, mean scores were 198 in the normal water, 205 in the supersaturated water. The difference is not significant ($t=0.43$).

Experiment 12. This experiment was actually a part of experiment 15 and included the additional variable of light-dark adaptation. The three levels of oxygen concentration were low (mean=5.3 p.p.m., 63 percent saturation), saturated (mean =7.9 p.p.m., 93 percent saturation), and supersaturated (mean=21.8 p.p.m., 240 percent saturation). Herring which had been adapted 6 hours to light or darkness before each trial were tested at each level of oxygen, making six combinations of experimental variables, each combination replicated five times. The herring were taken from storage at 12 to 17° C. and 100 to 124 percent saturation of oxygen and exposed 6 hours to the experimental conditions before each trial. The mean scores for ten trials at each level of oxygen were 125, 138, and 123. The difference among them was not significant ($F=0.7$).

Experiment 13. The effects of light or dark adaptation were most pronounced during the first minute of exposure to the attracting light. Because this critical time period may not have been adequately monitored in the other experiments with oxygen concentration, observations were made on groups of 10 fish 15, 30, 45, and 60 seconds after the attracting light was turned on. The location of the light was alternated between right and left with each trial. Four trials were made each day; normally saturated and supersaturated water were used on alternate days. The sequence was repeated twice, making eight trials at each oxygen level, all at a mean temperature of 15.5 to 17.0° C., and mean oxygen concentrations of 7.3 p.p.m., 88 percent saturation and 16.8 p.p.m., 200 percent saturation. The mean scores of 31 and 29 were not significantly different.

The weight of evidence indicates that neither oxygen concentration nor percentage saturation has any effect on the attraction of herring to light.

EFFECT OF PREVIOUS ADAPTATION

Experiment 14. Preliminary observations showed a tendency for herring to be less strongly attracted to light if they had been kept in darkness beforehand. Therefore, for most of the experiments the herring had been held in full room illumination so that their response would be as strong as possible. Nevertheless, some specific tests seemed desirable to confirm the preliminary observations.

Sixteen trials, two each day, were made with groups of 10 herring at a temperature of 5° C. Each group was exposed to a medium-intensity, underwater light after a 3-hour period of adaptation to light or darkness just before each trial. These adaptation periods were alternated with respect to time of day, forenoon or afternoon.

Because the fish had necessarily to be held at all times other than the 3-hour adaptation period at some lighting condition or another, the possibility existed that whatever this lighting was would also influence the subsequent behavior of the fish. Therefore, half of the trials were preceded with exposure to total darkness the night before and half with full illumination. The 16 trials were arranged as follows: eight in the morning and eight in the afternoon; four of each of these eight were preceded with a 3-hour period of darkness, and four with a 3-hour period of light; two of each of these four followed an overnight period of darkness and two an overnight period of light. An analysis of variance showed significant variation only with respect to the 3-hour pretrial light- or dark-adaptation period ($F=5.8$, $P=0.05$). The effects of overnight lighting and time of day were of doubtful significance ($F=3.4$, $P=0.1$, and $F=2.6$, $P>0.1$, respectively). The scores are shown in table 6. Pretrial adaptation to darkness reduced the effectiveness of light attraction.

TABLE 6.—*Comparison of scores*[1] *for light attraction of herring in relation to prior light experience and time of day (experiment 14)*

Time of day	Overnight darkness		Overnight light	
	Dark[2]	Light[2]	Dark[2]	Light[2]
AM	103	90	127	205
	105	153	132	134
PM	100	168	146	193
	155	162	136	170
Mean score	114	143	128	175

[1] Score=sum of numbers of herring counted in the illuminated half of the tank at 30 1-minute intervals. Ten herring were used in each test; maximum possible score=300.

[2] Light condition for 3 hours preceding trials.

Experiment 15. This experiment was done later in the year than experiment 14 at the higher temperature range of 15 to 17.5° C. No allowance was made for any previous light experience of the fish prior to a 6-hour light or dark period of adaptation before each trial. The experiment also included the additional variable of oxygen concentration and was actually a part of experiment 12. The mean score for 15 trials preceded by a 6-hour dark period was 122; that for 15 trials preceded by a 6-hour light period was 136. The difference between them was not significant ($F=1.48$, $P>0.2$). Apparently, previous adaptation to light or dark makes little difference in the response of herring to light at high temperature.

Experiment 16. The pretrial adaptation of herring to light produced the strongest positive response when the trials were made at low temperature. The most marked attraction in experiment 14 occurred during the first minute of the trial: the scores during the first minute differed by 57 percent; the total scores differed by only 25 percent. This fact suggests that light or dark adaptation affects the initial attraction to light more than it affects the tendency for the light to hold the fish.

Although the total scores at high temperature in experiment 15 did not differ significantly between light- and dark-adapted herring, the first minute scores were somewhat (though not significantly) higher for light-adapted herring. Experiment 16 demonstrated that the first minute scores for light-adapted herring were, in fact, significantly higher even at high temperature than those for dark-adapted herring. Four trials at 15 to 17.5° C. were made each day for 4 days; each trial was preceded by a 1-hour period of light or darkness. Counts of the fish were made at 15, 30, 45, and 60 seconds after the attracting light was turned on. The end of the tank illuminated, left or right, was alternated with each trial. The mean score for the fish adapted to light for 1 hour was significantly higher ($F=32.7$, $P<0.01$) than the mean score for the dark-adapted fish (table 7). A significant bias for one side of the tank also was apparent in this experiment. Such a bias sometimes occurred for unknown reasons and made left-right alternation of the illuminated side of the tank a necessary part of the procedure in all experiments.

This experiment showed that previous adaptation to light increases the initial attraction of the herring to light regardless of temperature; on the other hand, the holding effect of the light was weakened at high temperature regardless of the prior adaptation.

TABLE 7.—*Comparison of scores*[1] *for light attraction of herring during first minute of exposure, in relation to prior light experience (experiment 16)*

Location of light	Herring	
	Light adapted	Dark adapted
Left	31	36
	37	33
	29	25
	34	21
Right	23	5
	30	5
	30	10
	33	7
Mean score	31	18

[1] Score = sum of numbers of herring counted in the illuminated half of the tank at four 15-second intervals. Ten herring were used in each test; maximum possible score = 40.

ANALYSIS OF BEHAVIOR IN RESPONSE TO LIGHT

The attraction of herring to artificial lights is a composite behavior pattern made up of two general categories of responses: those that draw the fish toward the light and those that hold the fish under the light's influence. The initial attraction seems to be a (usually) positive telotaxis, defined by Frankel and Gunn (1961) as direct attainment of orientation, without deviations, to a source of stimulus as if it were a goal. This response is stronger in some individuals than in others and in a few may even be negative (away from the light).

The holding power of the light, on the other hand, is determined by several, often dissimilar, responses of the fish. One of these is the dorsal light reaction discussed earlier; it holds the fish near the light by interfering with normal swimming movements which would lead to escape. Another is photokinesis, where general activity and swimming speed increase with increasing light intensity; this response works in opposition to the dorsal light reaction, tending to cause dispersal. Adaptation and fatigue probably accompany continued exposure to the light and may weaken both of the other reactions. Finally, there is the startling or shock effect of sudden changes in light intensity, which may repel the fish, as if by fright.

The response of fish to light is determined by the way in which conditions influence these behavioral components. Some of these reactions can be summarized as follows: Temperature affects primarily the degree to which the fish are held under the influence of the light, probably through its effect on their activity; higher temperature increases general activity, which in turn tends to cause dispersal. The position of the light above or below the surface also affects the holding power of the light. Herring are accustomed naturally to light rays directed downward from the surface, and light from a source below the surface is likely to produce orientation which interferes with normal swimming and escape from the lighted zone. Previous adaptation affects primarily the initial attraction to the light, which is stronger in light-adapted fish than in dark-adapted fish.

An attempt to measure the startle effect of light indicated that whenever the attraction or holding power of the light was strong, the startle effect was less pronounced than when the attracting or holding power was weak. The startle effect was measured by the ratio of the number of fish in either side of the tank before the light was turned on to the number present immediately afterwards. A correlation of -0.957 was found between these ratios and the scores for 10 experiments selected to include those circumstances favorable to light attraction and those unfavorable.

The difference in response to light shown by individual fish and by fish in groups under otherwise similar conditions may be another significant aspect of behavior. The data from experiment 1, in which the responses of 90 individual herring to light were tested at three different temperatures, and from experiment 6, in which the responses of 90 herring were tested in groups of 10 at the same three temperatures are an example. If the fish tested individually are combined arbitrarily into three groups of 10 for each temperature, and the mean score for each group is expressed as a percentage of the maximum possible score, measures of variance among the groups can be calculated. Similarly, the variance among the scores, expressed as a percentage of the maximum possible score, can be calculated for the actual groups of 10 fish observed in experiment 6. A comparison shows that the variance among the scores of the actual groups of 10 fish is significantly greater than the variance among the scores of the arbitrarily created groups of fish tested individually. In fact, the variance among the scores of the actual groups is not significantly different from the variance among the scores of individuals. These facts imply that the collective response of 10 herring in a group is not simply an average of their individual responses. Instead, the collective response seems to reflect the individual responses of only one or two fish in the group.

To explain the apparent lack of thermal influence on fish individually in contrast to the significant thermal influence on groups, I suggest the following hypothesis. Most herring are only feebly influenced by temperature in their response to light. The preponderance of fish in this category causes the average response to appear uninfluenced by temperature when each fish responds as an individual, even though a few individuals may be strongly influenced. When the fish are in groups, however, the weakly influenced majority respond not so much to the stimulus itself as to the strongly influenced minority, whose behavior dominates the group. I believe that in this interaction lies the significance of the school in fish behavior: the interaction provides to the group a sensitivity and an ability not possessed by individuals to react in an unequivocal manner to a situation.

RESPONSES OF HERRING TO LIGHT AND THEIR APPLICATION IN THE FISHERY

Without doubt attraction to artificial lights at night is a significant behavioral response of herring, and it is potentially useful in the herring fishery. The question is: Under what conditions is this response brought out most strongly and what tactics in using lights can be most effectively employed?

Most of the evidence indicates that a submerged light is more effective than one above the surface. One reason is that the entire output of the underwater light is used, whereas a large portion of the light from above the water is reflected from the surface. The submerged light is also more uniform: the rays do not flicker from the effect of a ruffled surface. Moreover, the submerged light has an improved attracting effect which is independent of its greater efficiency. A submerged light which produced only 1/10 to 1/1,000 the underwater illumination of a light above an unruffled surface proved to be the more effective in laboratory experiments. Because of refraction, the rays from a light above the surface project sharply downward, even at some distance from the light source. It may be that the direction of the rays in relation to the position of the fish are important, and that rays from above the surface approaching the vertical tend to repel herring. The light from the sun, sky, or a bright moon would be of this nature; all of these light sources tend to keep the herring from the surface and may be the cause of the characteristic diurnal vertical migrations of herring.

Evidence from my experiments and also from other studies shows that the brightest lights are not necessarily the most effective for attracting herring. Although a brighter light will have a greater range and can be seen by fish at a greater distance, the illumination within a certain radius may exceed the optimum and tend to repel the fish even if they are attracted up to that radius. To obtain maximum range while still attracting nearby fish, certain manipulations of the light have been used effectively. The simplest method is to dim the light gradually (Gauthier, in press; Kurc, in press; Ström, in press). Another scheme was described by Sasaki (1959): A series of lights of optimum brilliance extend some distance from the fishing operation. The outermost light is turned on for a time until a substantial number of fish are attracted. This light is then extinguished, and another somewhat closer to the fishing operation is illuminated. Each light in the series is lighted and extinguished in sequence, attracting in turn the fish gathered about the preceding one.

Besides the properties of the light itself, certain factors of the environment govern the effectiveness of the light, especially in relation to the time of day or time of year it is used. Kawamoto (1959) showed that in some species of fish the light-seeking tendency was stronger in the daytime than at night. Tamura (1959), discussing this phenomenon and certain physiological changes in the eye of the fish when adapted from light to darkness, suggested "this may be one of the fundamental reasons why fishing with the use of light is usually more effective before than after midnight." The results of my own experiments with herring show a greater attraction to light of light-adapted fish, especially the initial attraction. All of these observations suggest that fishing with a light would be most effective shortly after dusk.

I can find no reference to the effect of temperature on the response of herring to light except as it relates to their passage through the thermocline; there are records, however, indicating that temperature does affect the response to light of other species of fish. Andrews (1946) showed that the positive phototaxis of suckers (*Catastomus*) was weakened at high temperature; Grubišić (1962) stated that the attraction of sardines (*Sardina pilchardus*) to light was weaker in the summertime than at other seasons and that this weakness was "more evident when the summers are more than normally hot."

Because the attraction of herring to light seems also to be weakened at high temperature, success in fishing for them with artificial lights might well depend in part on the season of the year and the temperature characteristics of particular localities. Moreover, temperature seems not only to affect directly the attraction to light, but also to modify the effects of light position and previous adaptation to light or darkness.

My purpose in the experiments involving temperature was limited to finding out whether temperature had any effect at all. Obviously, it did, but the critical values of both experimental and adaptation temperatures need yet to be defined. It is possible that the temperature preferendum described elsewhere (Stickney, in press) represents the critical point above which the light response weakens.

The use of lights in the herring fishery of the Canadian and United States Atlantic Coast has been in disfavor for some time and is even illegal in many places. Even where it is still legal, it is a method of little importance probably because fishermen believe that lights frighten the herring away (Scattergood and Tibbo, 1959). Fishing at night is carried on with as little light showing as possible. Because above-water lights, excessively bright lights, and lights suddenly flashed on or moved about do apparently frighten herring, the caution used in showing lights is probably justified. On the other hand, practical experience and biological evidence indicate that lights properly used under some circumstances can attract herring effectively. It would seem that artificial lights used in accordance with what is known about herring behavior would provide an extremely useful method for controlling the herring schools so that they would be in locations most conducive to setting purse seines or stop seines around them.

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