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Environmental Science & Policy 3 (2000) S393–S403

Environmental Science & Policy

www.elsevier.com/locate/envsci

Avoidance behavior of *Morone americana, Leiostomus xanthurus* and *Brevoortia tyrannus* to strobe light as a method of impingement mitigation

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Abstract

The use of strobe lights and strobe light-bubble curtain combinations were evaluated as behavioral guidance systems to reduce impingement via avoidance behavior by estuarine fish. White perch (*Morone americana*), spot (*Leiostomus xanthurus*) and menhaden (*Brevoortia tyrannus*) were tested in an experimental flume for avoidance to strobe lights, bubble curtains and strobe light-bubble curtain combinations at different water velocities, strobe flash rates and light acclimation (light and dark). The possible accommodation of fish to strobe light was also tested using a microcomputer and on-line biomonitoring chamber examining alterations in breathing rates over time. Avoidance of strobe light ranged from 8–36% for white perch, 8–100% for spot and 8–68% for menhaden depending on the conditions tested. Statistical analyses indicated significant avoidance by white perch at most flash rates with a 0.2 ms^{-1} flow rate and at 120 and 300 flashes min^{-1} with 0.3 and 0.5 ms^{-1} flows. Spot had significant avoidance under most conditions. Menhaden had significant avoidance for all flash rates at 0.2 ms^{-1} flows and for 300 and 600 flashes min^{-1} at flows of 0.3 and 0.5 ms^{-1}. All species exhibited little avoidance of bubble curtains alone. Strobe light-bubble curtain combinations had avoidance results of 3–58% for white perch, 21–85% for spot and 9–81% for menhaden. Spot and menhaden exhibited significant avoidance for most conditions at 0.2 and 0.5 ms^{-1} flows. White perch had significant avoidance for most conditions at 0.2 ms^{-1} flows, but no avoidance at 0.5 ms^{-1}. The biomonitoring system indicated that little, if any, accommodation took place during 24 h. Strobe light and strobe-bubble curtain combinations elicited the highest avoidance results at flash rates $\geq$300 min^{-1} and low water velocities. Strobe light systems may reduce impingement rates but must be evaluated on site specific needs and conditions. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Impingement; Mitigation; Avoidance; Strobe light; Bubble curtain; Behavioral guidance system

1. Introduction

The use of behavioral systems in fish management programs has received increased interest. Light is a primary stimulus for fish. Blaxter (1975) presented evidence that taxes to light occur among many fish species, which may be broadly classified as 'photopositive' or 'photonegative'. Blaxter (1975) concluded that light is the dominant stimulus in diel vertical migrations. Other investigators have found that certain fish species have preferred light intensities (Girsa, 1969; Whitney, 1969; Pavlov et al., 1972; Kwain and McCauley, 1978) that may alter other behavioral actions. The use of lights to increase commercial fish catches (Hunter, 1968; Solov'ev, 1971; Zilnov, 1971; Yami, 1976; Loesch et al., 1982) or to direct fish move-

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PII: S1462-9011(00)00046-0

ments (Wickham, 1973) in open waters has been investigated.

Many fish species have a light intensity threshold for the ability to maintain schools (Whitney, 1969). Some may require light to properly orient to currents and space and to maintain swimming activity (Pavlov, 1966; Suburenkov and Pavlov, 1968; Pavlov et al., 1972; Savchenko et al., 1982). Without visual cues they drift with currents and in the case of power plants will not actively avoid water intake structures. Behavioral barriers and/or guidance systems might lose effectiveness without the necessary illumination to enable fish to orient to and avoid the barrier. However, fish may be attracted to areas where lighting is present. Hadderingh (1982) found that illuminating the intake area of a power plant reduced impingement for certain species but increased it for others. Sager et al. (1985) established the existence of preferred wavelengths of light for juvenile menhaden and speculated on its use in guidance systems.

A review of behavioral methods used to reduce fish impingement rates at water intake structures is given in Hocutt (1980), Hocutt and Edinger (1980) and Popper and Carlson (1998). These methods include electrical barriers, air-bubble curtains, illumination, acoustic barriers and current-related structures. Hocutt (1980) found behavioral guidance systems had only 'marginal success' but attributed this in part to the lack of novel approaches which used key environmental stimuli on basic behavioral responses. Popper and Carlson (1998) found that no behavioral control method will be successful unless the behavior of the species is understood in each place it is to be applied.

Studies have been undertaken on whether flashing lights would cause avoidance reactions by fish due to light stimuli not normally experienced by fish. Fish encounter flashing light in the environment from atmospheric and water-surface effects causing light fluctuations (Dera and Gordon, 1968; McFarland and Loew, 1983). Patrick et al. (1985) and Sager et al. (1987) reported that fish avoided strobe light and strobe light-bubble curtain combinations. A strobe light stimulus would provide the light necessary for fish orientation but still be an abnormal light stimulus.

For a guidance system based on behavioral reactions to be successful the reactions must be sustained over fairly long periods of time. If fish accommodate to the stimulus prior to reaching the desired location, the system will be ineffective. Gill ventilation rates have long been used to measure the stress fish experience, or a reaction to a stimulus (Cairns et al., 1970, 1982; Spoor et al., 1971; Heath, 1972; Szyper and Lutnesky, 1991; Wingard and Swanson, 1992; Knoph, 1996; Sager et al., 2000). Methods for this practice have progressed from direct observation of fish to the use of sophisticated electronic equipment to monitor electromyograms (EMG) generated from the electrical activity of opercular and buccal muscles during ventilation (Heath, 1972; Spoor et al., 1971; Cairns et al., 1980; Capute, 1980). With advances in electronics, the use of submerged electrodes, instead of electrodes attached to the fish to monitor EMG, electronic systems became accurate and automated through the use of better amplifiers (Gruber et al., 1977) and on-line computer systems (Cairns et al., 1980; Cairns and Gruber, 1980) that do not need constant observation or supervision. Such biomonitoring units offer advantages for experiments over long periods of time. Sager et al. (2000) demonstrated that an on-line biomonitoring system detected alterations in ventilation rates (breathing rates) in reaction to strobe light stimulus.

This paper reviews the literature and results of the studies by Sager et al. (1987, 2000) on the potential to use strobe lights and strobe light-bubble curtain combinations in behavioral guidance systems for estuarine fish. Specific objectives include examining the reactions of white perch (*Morone americana*), spot (*Leiostomus xanthurus*) and menhaden (*Brevoortia tyrannus*) as representative species to strobe light and strobe light-bubble curtain combinations as potential guidance systems (Sager et al., 1987). Reactions under light and dark conditions with various water flow rates will be reviewed. Since a behavioral guidance system can only be successful if the behavioral reactions last long enough for the fish to move away from the intake system, potential accommodation to strobe light has been examined (Sager et al., 2000).

2. Methods

2.1. Flume studies

A more detailed explanation of the flume method used is provided in Sager et al. (1987). Subadult white perch, spot and menhaden were collected from Chesa-

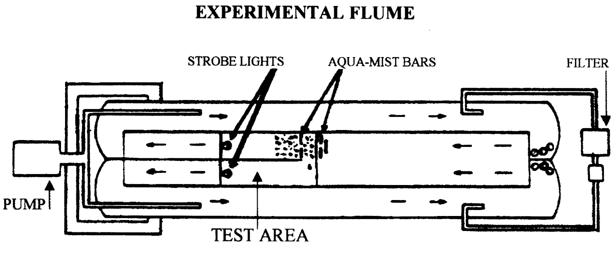

Fig. 1. Experimental flume for avoidance behavior tests. The test area was monitored by a closed-circuit TV camera above the strobe lights. The arrows indicate the direction of water flow.

peake Bay tributaries, mainly the Choptank River, for the experiments.

A behavioral test flume (Fig. 1) that could deliver water at regulated flow rates was used to determine fish reactions. Diffusers and baffles were used to promote an evenness of flow. A test area was established within the chamber using screens. The test area was divided into equal-sized right and left channels by a solid partition set parallel to the direction of the water flow to within 25 cm of the upstream screen barrier. Tandy xenon strobe lights in waterproof containers were mounted in the water column of each channel. The strobe lights could be individually controlled and operated at various flash frequencies. A remote-controlled Javelin low light camera with zoom lens and a Sony videocassette recorder enabled the recording of all tests for later analysis. Bubble curtains were established in the experimental flume via Aquamist Bars placed on the bottom of the test chamber. The test room could be illuminated for normal light or low light (dark) experiments. Low light conditions were established through the use of red fluorescent lights. Total dark could not be used since the camera system required some light to function. The red fluorescent lights had a peak wavelength of 630 nm, with 98% of the light emitted between 600 and 750 nm, which is near the upper limit of sensitivity for most fish (Ali and Antcil, 1976; Levine and MacNichol, 1979). Therefore, fish would perceive much less light than under the white light system. Light intensities in the test area of the flume averaged 0.8 $\mathrm{Em}^{-2}\ \mathrm{s}^{-1}$ for white light and 0.14 $\mathrm{Em}^{-2}\ \mathrm{s}^{-1}$ for red light (dark) conditions. Light intensities were measured with a Li-Cor, Inc. Model LI-185B radiometer equipped with a quantum sensor. Test specimens were acclimated to light or dark conditions for a minimum of 3 days prior to testing.

Fish were tested in groups of five to account for schooling behavior. The fish were acclimated to the test flume for a minimum of 20 min before tests were initiated. The flow rate to be tested was then initiated and the positions of the fish recorded for 1 h. Strobe light-bubble curtain conditions were then initiated in one of the channels and the reactions of the fish were recorded for another 1 h period. Because of the lower swimming efficiency of white perch, experiments on this fish used 0.5 h intervals.

Tapes of the experiments were reviewed and the position of the fish noted at 5 min intervals (2.5 min for white perch). The positions prior to initiation of the strobe light-bubble curtain conditions was used as the expected distribution of the fish and compared to the distribution after initiation via Chi-square analysis ($P < 0.05$). Four replicate tests were conducted for each experimental scenario tested.

2.2. Accommodation experiments

Experiments were conducted by monitoring change in gill ventilation rates (breathing rates) of fish subjected to xenon strobe lights or unexposed fish (Sager et al., 2000). Electrical impulses generated by gill ventilation were received via top and bottom submerged stainless steel electrodes in test aquaria in which a fish was held (Fig. 2). Signals (EMG) were amplified (using an amplifier modified from Gruber et al. (1977), were recorded on a Honeywell chart recorder and interfaced (via a Starbuck Analog-Digital converter) with an IBM compatible microcomputer. Ventilation rates were recorded for every other minute. These data were stored on microcomputer disks for later analysis and a hard copy of the data was printed. The experimental system was modeled after systems in use as biomonitoring stations (Cairns et al., 1980; Cairns and Gruber, 1980), but was modified to use top and bottom mounted electrodes as recommended by Capute (1980).

Specimens of white perch and spot were tested under constant light conditions to eliminate changes in ventilation rates resulting from changes in light levels (photoperiod). A total of 10 specimens for each species were tested under continuous light or dark conditions. Specimens were held for at least 3 days in freshwater conditions under the light conditions for the test to allow the specimens to acclimate. One specimen was introduced into the test aquaria and allowed to acclimate for 48 h. Thereafter, the amplifier, chart recorder and microcomputer were activated; the data handling program initiated; and the experiment started. The ventilation rate of the specimen was recorded for 24 h as the base ventilation rate. The strobe light was then initiated and the ventilation rate recorded for 24 h to indicate the ‘stressed’ ventilation rate exhibited by that specimen. Experiments were conducted at a strobe flash frequency of 300 flashes min^{-1} because this frequency was found to elicit a consistent avoidance response by spot and white perch in other studies (Patrick et al., 1985; Sager et al., 1987).

Chi-square analyses were conducted on the change in mean ventilation rates for each specimen. Data were also analyzed by comparing paired observations of the base ventilation rate to the ‘stressed’ rate for the same 30 min interval over the 24 h test periods. Differences between paired observations for each 24 h baseline (expected distribution) and ‘stressed’ (observed distribution) ventilation rate were analyzed. Thirty minute intervals were used to reduce variation in the data set, as noted by Gruber and Cairns (1981). All analyses used a significance level of $P < 0.05$. If the ‘stressed’ ventilation rate returned to the base rate over time, accommodation to the strobe light would be indicated.

3. Results

3.1. White perch

White perch exhibited variable avoidance behavior to strobe lights alone under the conditions tested (Table 1). White perch partially avoided strobe lights for all experiments at the 0.2 ms^{-1} water flow rate, with a decreased use of the strobe lit area of the experimental flume from 10 to 36%. White perch avoidance decreased at the higher velocities from 12 to 22% at 0.3 ms^{-1} and from 8 to 24% at 0.5 ms^{-1}. Chi-square analyses indicated significant results for light acclimated white perch at 120 and 300 strobe flashes min^{-1} and for dark acclimated specimens at 300 and 600 flashes min^{-1} with a flow of 0.2 ms^{-1} (Table 2). Only light acclimated white perch at 120 and 300 flashes min^{-1} exhibited significant avoidance at the 0.3 ms^{-1} flow rate. The 0.5 ms^{-1} current experiments yielded significant results for light acclimated white perch at 120 flashes min^{-1} and dark acclimated specimens at 300 flashes min^{-1}.

In experiments with bubble curtains and strobe light-bubble curtain combinations, white perch exhibited at attraction to bubble curtains alone of 11–26% at 0.2 ms^{-1} and 9–35% at 0.5 ms^{-1} (Table 1). Combinations of strobe lights with bubble curtains resulted in avoidance rates of 7–58% at all combinations with flow rates of 0.2 ms^{-1}. Experiments at 0.5 ms^{-1} gave mixed results with no, or low (3–6%) avoidance. Significant avoidance was indicated for strobe light-bubble curtain combinations (Table 2), while significant attraction was found for the bubble curtain alone (at 0.2 ms^{-1} flows).

In accommodation experiments, white perch baseline ventilation rates ranged from 1 to 97 counts min^{-1} (cpm) with an overall mean of 41 cpm (Fig. 3). Mean stressed rates for light acclimated specimens ranged from 1 to 100 cpm with an overall mean of 44 cpm. Mean baseline rates for dark acclimated specimens ranged from 1 to 79 cpm with an overall mean of 35 cpm. Mean stressed rates for dark acclimated specimens ranged from 2 to 83 cpm with an overall mean of 30 cpm. Presenting the change in ventilation rates from baseline to stressed conditions as an absolute value, for the difference, aids in removing some difficulties in interpreting the data. Since individual specimens varied in how their ventilation rates were altered, using absolute values eliminates negative and positive changes from canceling each other out in developing data means. Light acclimated white perch had absolute differences ranging from 0 to 43 cpm with an overall

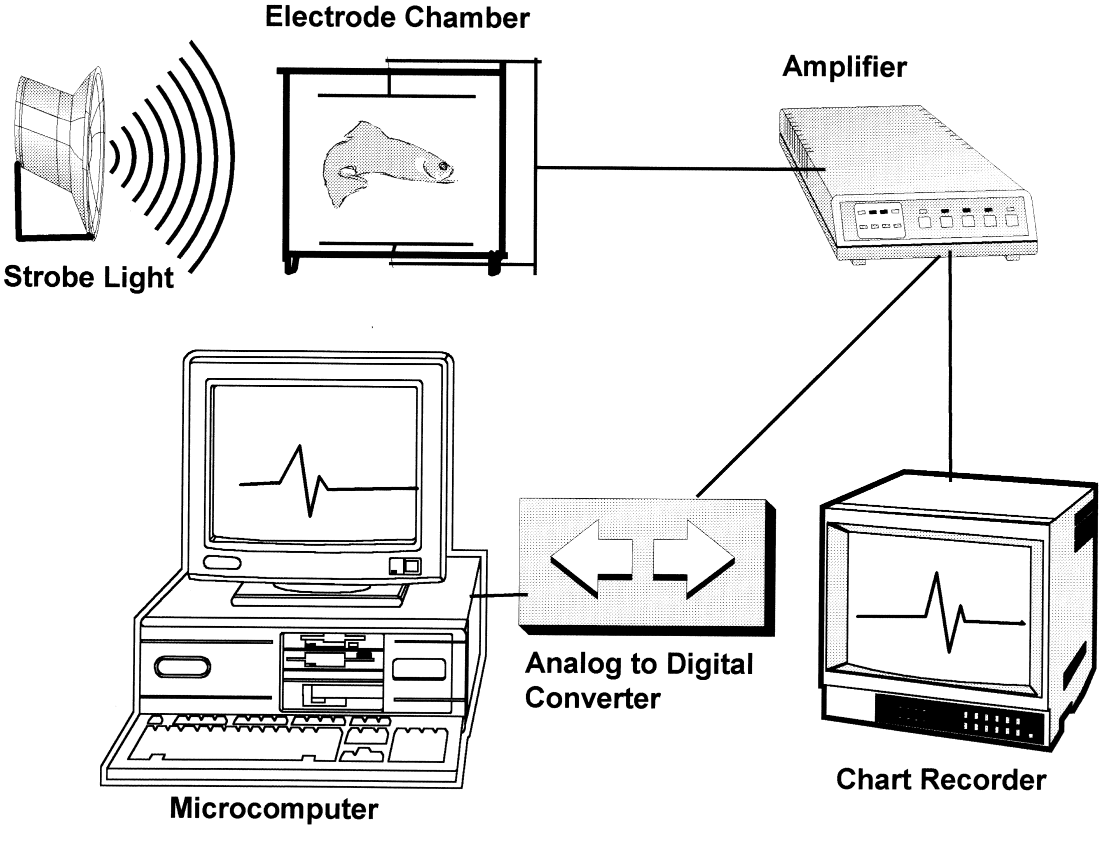

Fig. 2. Schematic of the biomonitoring system components.

Table 1
Percentage reduction in usage of the strobe lit area of the test flume at different water flow rates, strobe flicker frequencies and light acclimation using (a) strobe lights alone and (b) strobe light-bubble curtain combinations for white perch, spot and menhaden[a]

Acclimation/Flow rate (ms^{-1})	Bubbles only	Flicker frequency (flashes min^{-1})		
		120	300	600
White Perch, *Morone americana*				
(a) Light acclimated				
0.2	–	20	36	12
0.3	–	17	22	12
0.5	–	15	9	−5
(a) Dark acclimated				
0.2	–	10	9	32
0.3	–	10	−1	18
0.5	–	8	24	−3
(b) Light acclimated				
0.2	−11	23	36	7
0.5	−35	−16	6	−7
(b) Dark acclimated				
0.2	−26	9	58	37
0.5	−9	−16	−8	3
Spot, *Leiostomus xanthurus*				
(a) Light acclimated				
0.2	–	21	9	100
0.3	–	−23	20	50
0.5	–	30	12	44
(a) Dark acclimated				
0.2	–	37	79	73
0.3	–	−12	50	69
0.5	–	17	57	39
(b) Light acclimated				
0.2	10	24	63	56
0.5	−19	46	45	33
(b) Dark acclimated				
0.2	−8	21	85	69
0.5	−9	−6	24	−15
Menhaden, *Brevoortia tyrannus*				
(a) Light acclimated				
0.2	–	22	17	9
0.3	–	−53	27	9
0.5	–	11	15	22
(a) Dark acclimated				
0.2	–	19	11	19
0.3	–	−7	8	68
0.5	–	17	37	22
(b) Light acclimated				
0.2	25	22	67	52
0.5	0	9	19	48
(b) Dark acclimated				
0.2	9	18	81	34
0.5	28	11	51	42

[a] Negative values indicate attraction not avoidance (increase in area use).

mean of 11.01 cpm. Differences for dark acclimated specimens ranged from 0 to 78 cpm with an overall mean of 11.13 cpm. Statistical analyses indicated significantly different results for all specimens tested, except for one light acclimated specimen. All 0.5 h intervals of light and dark acclimated specimens were significantly different.

3.2. Spot

Spot exhibited avoidance to strobe lights under all conditions at the 0.2 ms^{-1} flow rate with decreases of 9 to 100% (Table 1). Spot had avoidance at the 0.3 ms^{-1} flow for 300 and 600 flashes min^{-1} with decreases of 20–69%, but exhibited attraction for 120 flashes min^{-1} (12–23% increase). Avoidance was

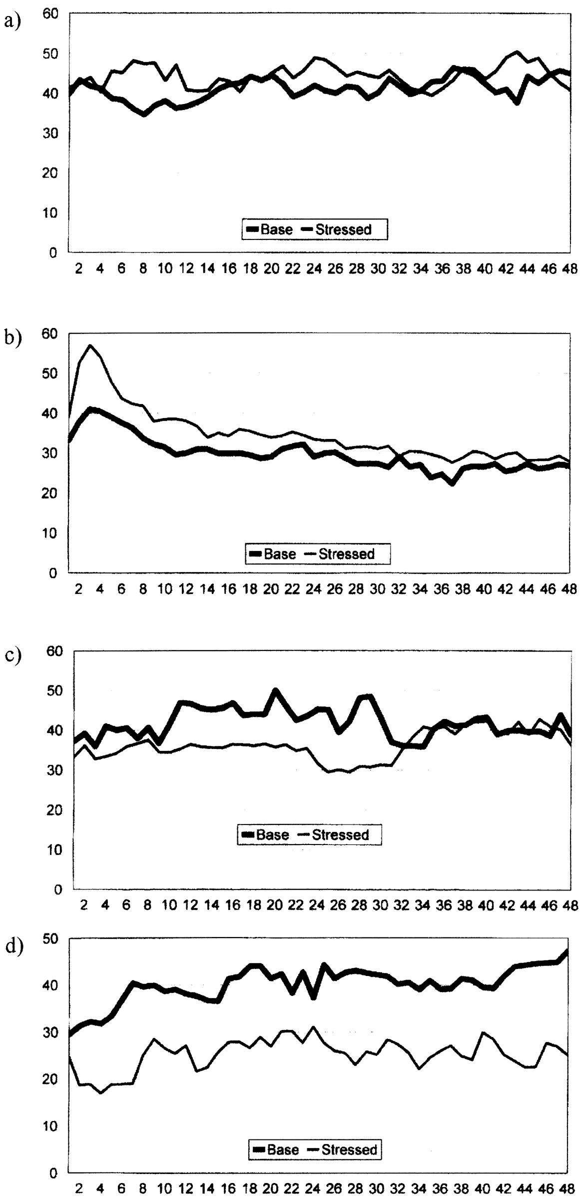

Fig. 3. Overall mean ventilation rates (cpm) for the 48 0.5 h intervals over the 24 h experiments for 10 specimens under baseline (thick line) and stressed (thin line) conditions for: (a) light acclimated white perch; (b) dark acclimated white perch; (c) light acclimated spot; and (d) dark acclimated spot.

exhibited under all conditions at the 0.5 ms^{-1} flow, with decreases of 12–60%. Statistical analyses had significant avoidance results for most conditions (Table 2), except for the 120 flashes min^{-1} at 0.3 ms^{-1} current, when significant attraction occurred.

Spot gave inconsistent results for bubble curtains alone with changes ranging from a 10% decrease to 8–19% increases (Table 1). Spot avoided all strobe light-bubble curtain combinations at the 0.2 ms^{-1} flow with 21–85% decreases. Spot avoided most combinations at the 0.5 ms^{-1} current (24–46% decrease), except for dark acclimated specimens at 120 flashes min^{-1} (6% increase) and 600 flashes min^{-1} (15% increase). Significant avoidance was indicated under almost all conditions the 0.2 ms^{-1} water velocity, except for experiments with only bubble curtains (Table 2). The strobe light-bubble curtain experiments had significant avoidance indicated at the 0.5 ms^{-1} current, except for dark acclimated specimens at 120 and 600 flashes min^{-1} and for experiments with only bubble curtains.

In accommodation experiments, spot had mean baseline ventilation rates of 3–146 cpm (overall mean of 42 cpm) for light acclimated specimens (Fig. 3) and 1–94 cpm for dark acclimated specimens (overall mean of 40 cpm). Stressed rates for light acclimated specimens had a range of 2–134 cpm (overall mean of 36 cpm), while dark acclimated specimens had a range of 1–72 cpm (overall mean of 25 cpm). Spot had absolute differences between baseline and stressed conditions of 0–101 cpm (overall mean of 14.68 cpm) for light acclimated specimens while dark acclimated spot differences ranged from 0 to 70 cpm (overall mean of 20.56 cpm). Statistical results indicated significant differences for all dark acclimated specimens and all but one light acclimated specimen. Analyses of time intervals had significantly different results for all intervals.

3.3. Menhaden

Menhaden exhibited consistent avoidance of strobe light under all conditions tested. Decreases ranged from 9 to 68%, with most values near 20% (Table 1). The only major exception took place for 120 flashes min^{-1} at the 0.3 ms^{-1} current where attraction (7–53%) rather than avoidance was indicated. Significant results were found at the 600 flash min^{-1} strobe rate under all flow conditions (Table 2). All flash rates yielded significant results at the 0.2 ms^{-1} flow rate. Significant avoidance was also indicated at 300 and 600 flashes min^{-1} at the 0.5 ms^{-1} flow rate. Menhaden avoided bubble curtains and strobe-bubble curtain

Table 2
Statistical results for Chi-square analyses for avoidance behavior by three estuarine fish species to (a) strobe light and (b) strobe light-bubble curtain combinations at different water flow rates, flicker frequencies and light acclimation procedures[a]

Acclimation	Strobe flicker frequency (flashes min^{-1})							
	0		120		300		600	
	Light	Dark	Light	Dark	Light	Dark	Light	Dark
Flow rate (ms^{-1})								
(a) White Perch, *Morone americana*								
0.2	–	–	13.0*	10.2*	25.3*	15.6*	2.7	11.7*
0.3	–	–	12.9*	5.6	10.0*	3.2†	4.4	6.7
0.5	–	–	8.5*	9.2*	6.3	9.5*	0.5†	1.4†
Spot, *Leiostomus xanthurus*								
0.2	–	–	8.0*	23.6*	5.7	104.7*	41.0*	64.9*
0.3	–	–	21.8*†	26.4*†	13.1*	63.5*	37.3*	42.5*
0.5	–	–	17.5*	29.6*	8.2*	60.5*	44.3*	36.1*
Menhaden, *Brevoortia tyrannus*								
0.2	–	–	10.4*	14.9*	15.8*	30.8*	9.4*	38.2*
0.3	–	–	23.5*†	6.3†	20.0*	3.0	8.3*	52.2*
0.5	–	–	1.9	5.4	14.8*	16.2*	16.0*	10.2*
(b) White Perch, *Morone americana*								
0.2	14.5*†	34.2*†	15.6*	13.4*	17.6*	47.1*	5.1	26.1*
0.5	29.0*†	3.3†	20.9*†	13.7*†	6.7	3.8†	3.1†	1.4
Spot, *Leiostomus xanthurus*								
0.2	2.6	7.8†	11.2*	17.5*	58.2*	79.3*	45.4*	56.0*
0.5	18.7*†	4.0†	40.0*	7.8†	29.4*	11.1*	30.0*	14.7*†
Menhaden, *Brevoortia tyrannus*								
0.2	11.8*	6.5	15.7*	7.5	66.5*	85.5*	43.9*	21.7*
0.5	0.8	16.8*	4.4	5.8	15.3*	35.3*	22.7*	30.1*

[a] Note: *Significant at $P < 0.05$ with 3 df. † Attraction indicated, not avoidance.

combinations under almost all conditions at the 0.2 ms^{-1} velocity (Table 2) with changes of 9–81%. Menhaden significantly avoided bubble curtains and strobe-bubble curtain combinations under all conditions at the 0.5 ms^{-1} flow rate (9–51%) except for at 120 flashes min^{-1} and light acclimated specimens with the bubble curtain alone. Significant results were obtained for all conditions at the 0.2 ms^{-1} current except for dark acclimated specimens at 0 and 120 flashes min^{-1} (Table 2).

4. Discussion

4.1. Strobe light

Phylogenetically related taxa are usually more similar functionally and are likely to have similar ecological requirements and thresholds (Stauffer and Hocutt, 1980; Hocutt, 1981). The results of this study are probably indicative of how other taxonomically related species would react to strobe lights.

The species tested represent a wide range of physiological and ecological adaptations. While each is a schooling species, menhaden are planktivorous and pelagic in nature. Spot and white perch are omnivorous, demersal species. White perch are more piscivorous than spot and utilize more of the water column (Hildebrand and Schroeder, 1972).

Each species exhibited avoidance behavior to strobe light. Evidence exists that avoidance of strobe light is related to flash rate and duration of the flash (in microseconds) rather than spectral composition of the light source (Patrick et al., 1985). The discharge of the strobe is very abrupt, unlike flickering light that is normal underwater and caused by wave and cloud action (Dera and Gordon, 1968; McFarland and Loew, 1983).

Differences in visual systems, stemming from phylogenetic and ecological characteristics may determine the degree of reaction to strobe light stimuli by fish (Sager et al., 1987). It is possible that the rod/cone ratio may be the controlling factor in the critical flicker frequency of vertebrate eyes influencing the fish's reaction to flash frequencies. The functioning of the retina in low light (scotopic) conditions is mediated by the rod system, while cones are the functional visual system during daylight (photopic) conditions. The rod/cone ratio may reflect the ability of the teleost eye to alternate between the two visual systems in flickering light. However, little data are available on the rod/cone ratios in teleost fish.

The species examined in these studies exhibited varying degrees of avoidance behavior as illustrated by the percent reduction in use of the strobe lit area (Table 1) and statistical results in Table 2. Avoidance rates decreased with increasing flow rates (Table 1). The three species varied in their ability to maintain position in the flow rates used in this study. Of the three species tested, white perch were the least capable of maintaining position in water currents. This species' inability to maintain position required that the experimental intervals be decreased for this species (see Section 2). Spot were able to maintain their position at the water velocities tested, but exhibited some difficulty at higher flow rates. There was usually a decrease in avoidance with increasing flow rates (Table 1). Menhaden had no difficulty in maintaining position in the water flow rates used in this study. No consistent decrease in avoidance was indicated by menhaden as a response to water velocity (Table 1). The pelagic lifestyle of menhaden, with the attendant body form (streamlining) and swimming ability, enabled this species to maintain their position in the water at all flow rates.

The species tested reacted to strobe light under both light and dark conditions. Impingement is usually greatest at water intake structures during twilight and/or dark conditions for most species. It is important that any behavioral system is effective under low light conditions. In these experiments, avoidance by dark acclimated specimens was usually equal to or greater than that of light acclimated specimens (Tables 1 and 2; Fig. 3). This increase in avoidance under low light conditions is an important improvement over other behavioral systems. A major constraint of behavioral systems has been that many lost effectiveness at low light levels probably because the fish did not receive the necessary illumination to orient and actively locate or avoid the barrier (Pavlov et al., 1972; Zweiacker et al., 1977; Hocutt, 1980).

Illumination is not the only consideration. Hadderingh (1982) illuminated the intake area of a power plant and found that impingement rates decreased for certain fish species, but increased for other species that were attracted to the light. Strobe light minimizes this problem. Strobe light provides illumination but has elicited avoidance reactions for all species tested in fresh and estuarine waters with over 200 flashes min^{-1}. Other light systems (mercury vapor, incandescent and fluorescent) used in flashing systems have not generated equivalent avoidance reactions as strobe light (Fields and Finger, 1956; Patrick, 1982, 1983). Obtaining avoidance reactions over extended time periods makes the strobe light system more likely to succeed as a guidance system at intake structures.

The flash rate of the strobe light influences the effectiveness of the system in obtaining an avoidance reaction. Avoidance was usually higher for flash rates greater than 120 per minute (Tables 1 and 2). The 120 flash rate was usually the only flash frequency to indicate significant attraction in these experiments. Table 2 indicates that significant avoidance for spot and menhaden were more common at the 300 and 600 flash rates, and at the 120 and 300 flash rates for white perch. Patrick (1982) found avoidance to strobe light increased at flash rates over 200 min^{-1} for species tested in freshwater systems. The higher flash rates should be utilized with the strobe light system to obtain the greatest, most consistent avoidance by estuarine fish.

The experiments on strobe light avoidance show that water flow velocities, strobe flash frequency and fish species influence the degree of avoidance exhibited. The results indicate that site specific considerations must be used in designing the best system to reduce impingement rates via strobe light guidance.

4.2. Strobe light-bubble curtain combinations

As predicted from earlier studies (Zweiacker et al., 1977; Lieberman and Muessig, 1978; Patrick et al., 1985), bubble curtains alone did not elicit consistent avoidance behavior (Tables 1 and 2). Spot and white perch were slightly attracted to the bubble barrier. Stupka and Sharma (1977) reported that bubble curtains were ineffective in keeping fish out of the intake of the Surry Power Station on the James River, Virginia. Bibko et al. (1974) established that illuminated bubble curtains were effective in guiding gizzard shad (*Dorosoma cepedianum*) and striped bass (*Morone saxatilis*). Patrick et al. (1985) showed that gizzard shad avoided bubble curtains, except under dark conditions. Patrick et al. (1985) also found that diversion devices illuminated by strobe light elicited increased avoidance behavior by freshwater fish over non-illuminated barriers in clear and turbid waters.

Light and dark acclimated specimens of all species tested in this study usually exhibited avoidance behavior to strobe light-bubble curtain combinations. Avoidance was often greater for dark acclimated specimens (Tables 1 and 2). As with the strobe light experiments, the flash rate of the strobe in the combination experiments gave variable avoidance rates. The results are similar to those for the strobe light alone. Avoidance was generally greatest at the 300 strobe flash frequency (Table 1). The decrease in avoidance at the 600 flash rate may be the result of the high flash rate and bubble curtain generating light near the critical fusion frequency for the visual systems of the fish. The critical fusion frequency is the flicker rate at which the visual system is unable to react quickly enough to differentiate between individual flicker stimuli. It is known that the critical fusion frequency varies among species, at different water temperatures and at different light intensities (Hanyu and Ali, 1963, 1964). Although exact data do not exist for most fish species, it is probable that the flash rate will reach a point of diminishing return with faster flash rates.

In most situations the combination of bubble curtains with strobe lights gave equal, or greater, avoidance rates as either the strobe lights or bubble curtain alone (Tables 1 and 2). The greatest increase in avoidance was by menhaden the more pelagic species. Sites with similar species of concern could well benefit from a combination system compared to strobe lights only.

Strobe light and strobe light-bubble curtain combination systems show promise as guidance systems for estuarine fish. However, systems must be designed for site specific requirements such as water flow rates, species of concern and best flash rates. As noted by Sullivan (1997), studies need to be conducted on systems placed into aquatic systems to fully determine whether strobe light systems are feasible.

4.3. Accommodation to strobe light

The biomonitoring system successfully recorded ventilation EMG signals from the fish tested. A bimodal signal was noted for the estuarine fish similar to the signals reported in Spoor et al. (1971), Gruber et al. (1979) and Cairns et al. (1980) and the signal varied between baseline and stressed conditions.

The study found that ventilation rates varied among individual specimens as well as among the species tested (Fig. 3). Baseline ventilation rates over the 24 h period of the experiments were fairly consistent for both species. The baseline ventilation rates for light acclimated white perch and spot had similar overall means (41 and 42 cpm, respectively), but the variation in rates was higher for spot. Ventilation rates were lower for dark acclimated specimens of both species (35 and 40 cpm, respectively). This is probably a reflection of the fish being more active under light conditions.

The alteration in ventilation rates by estuarine fish exposed to strobe light was similar to alterations obtained for fish exposed to sublethal concentrations of toxicants (Cairns et al., 1970; Lang et al., 1987), which found either increases, or decreases, from baseline (control) rates. Light acclimated white perch showed a varied reaction to strobe light above and below baseline rates resulting in means often similar despite significant differences by individual specimens (Fig. 3). Dark acclimated white perch exhibited a more consistent increase in ventilation rates resulting in a relationship indicating a large initial difference between baseline and stressed mean rates with a gradual decrease in the difference over time (Fig. 3). Spot exhibited a greater difference between base and stressed ventilation rates for both light and dark acclimated specimens. Light acclimated spot had mean stressed ventilation rates below base rates for 16 h after which the rates varied around each other. Dark acclimated spot mean stressed ventilation rates were lower than base rates and remained well below those rates for the entire 24 h period (Fig. 3). These results support findings of Patrick et al. (1985) and Sager et al. (1987) that specimens of these species exhibited greater avoidance reactions during low light level experiments, unlike other behavioral systems that were ineffective under dark conditions (Hocutt, 1980).

Patrick (1979a,b) attempted to address the accommodation to strobe light by fish through long-term experiments, or re-exposing previously tested fish to see if the reactions to strobe light would be repeated. The avoidance behavior was found to be continued, or repeated, for these experiments on gizzard shad (*Dorosoma cepedianum*). In the studies on spot and white perch, the estuarine species did not statistically accommodate to strobe light over the 24 h time periods of all test conditions. There were some visual indications that the differences between base and stressed ventilation rates decreased over time (Fig. 3). This indicates that accommodation may have been found if the experiments were over a longer time interval. Even the visual indication of accommodation illustrates that the reaction is sustained over several hours. This time period should be sufficient to direct the fish species away from water intake systems to decrease impingement rates.

The data for these estuarine fish indicate that migratory schools of the species tested could move through a strobe lit water intake area prior to accommodation taking place. These species react to strobe light over several hours and react well to the stimuli under dark conditions, unlike other behavioral systems.

5. Conclusions

The estuarine species tested (spot, white perch and menhaden) usually avoided strobe light and strobe light-bubble curtain combinations. Only menhaden avoided bubble curtains alone. The species tested exhibited variations in avoidance with water flow rates, strobe flash frequencies and light acclimation of the fish. Generally, avoidance was enhanced when strobe light-bubble curtain combinations were used, especially for pelagic species. Spot and white perch did not accommodate to strobe light, indicating avoidance behavior lasts for a sufficient time period to direct fish away from water intake systems. Avoidance under dark conditions is significant which is an improvement over most other behavioral systems. The experiments indicate a strobe light system would be most effective combined with bubble curtains, strobe flash frequencies of about 300 per minute and in low water current situations. Also, various species react differently to the strobe light stimulus exhibiting different levels of stress and avoidance behavior.

These conclusions indicate that strobe lights hold promise for behavioral guidance systems, but must be developed and designed to address site specific needs and limitations. Such systems will not exclude all fish from an area, but could significantly reduce the numbers at risk for impingement. As expressed by Popper and Carlson (1998), behavioral systems need to be examined in laboratory experiments, field experiments, basic and applied assessments in order to more fully understand their potential and limitations. Hopefully, field experiments, such as noted in Sullivan (1997), will build on the information provided by other experiments on strobe light guidance systems and increase our ability to determine the feasibility of such guidance systems to reduce impingement at water intake structures.

Acknowledgements

These studies were partially supported through research grants from the Potomac Electric Power Company and the Andrew J. Boehm Graduate Fellowship in Fisheries Science. We acknowledge the assistance given by associates (D. Rhoades, A. Akers, C. Baptist, R. Raesley, R. Jesien, J. Berg, S. Jordan and others) at the Horn Point Laboratories, Center for Environmental Studies, University of Maryland.

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