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Estuarine Fish Responses to Strobe Light, Bubble Curtains and Strobe Light/Bubble-Curtain Combinations as Influenced by Water Flow Rate and Flash Frequencies

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ABSTRACT

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This study examined the possible use of strobe lights and strobe light/bubble-curtaincombinations as behavioral guidance systems for estuarine fish. White perch (*Morone americana*), spot (*Leiostomus xanthurus*) and Atlantic menhaden (*Brevoortia tyrannus*) were tested in a behavior experimental tank for avoidance to strobe lights, bubble curtains and strobe light/bubble-curtain combinations at different water flow rates, strobe flash frequencies and light acclimations.

Percentage avoidance of strobe light ranged from 8 to 36% for white perch, from 8 to 100% for spot and from 8 to 68% for menhaden, depending on the conditions tested. χ^2 analyses indicated significant ($P < 0.05$) avoidance by white perch at most flash rates with a 0.2 m s^{-1} flow rate, and at 120 and 300 flashes min^{-1} with 0.3 and 0.5 m s^{-1} flows. Spot had significant avoidance for all flash rates at the 0.2 m s^{-1} flow, and for 300 and 600 flashes min^{-1} at water velocities of 0.3 and 0.5 m s^{-1}. All species showed little avoidance of bubble curtains. Avoidances of 3-58% for white perch, 21-85% for spot and 9-81% for menhaden were obtained with the strobe light/bubble-curtain combinations. χ^2 analyses indicated significant avoidance for most conditions at 0.2 and 0.5 m s^{-1} flows for spot and menhaden. White perch had significant avoidance for most conditions at the 0.2 m s^{-1} flow, but no avoidance at 0.5 m s^{-1}.

The strobe light and strobe light/bubble-curtain combinations elicited best avoidance results at flash rates of 300 min^{-1} or greater and low flow rates. Strobe lights show promise as a guidance system for estuarine fish.

INTRODUCTION

The use of behavioral systems in fish management programs has received increased interest. Light is a primary stimulus for fish. Blaxter (1975) presented

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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 movements (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 by illuminating the intake area of a power plant, impingement was reduced in certain species but increased in 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 by Hocutt (1980) and Hocutt and Edinger (1980). 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.

Researchers initiated studies on the possibility that 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) 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.

The study presented in this paper is a continuation of some of the research reported in Patrick et al. (1985). The objectives were to study the avoidance behavior of three estuarine fish species to strobe light and/or a bubble curtain at different water velocities, strobe flash frequencies and light conditions. White perch (*Morone americana*), spot (*Leiostomus xanthurus*) and Atlantic men-

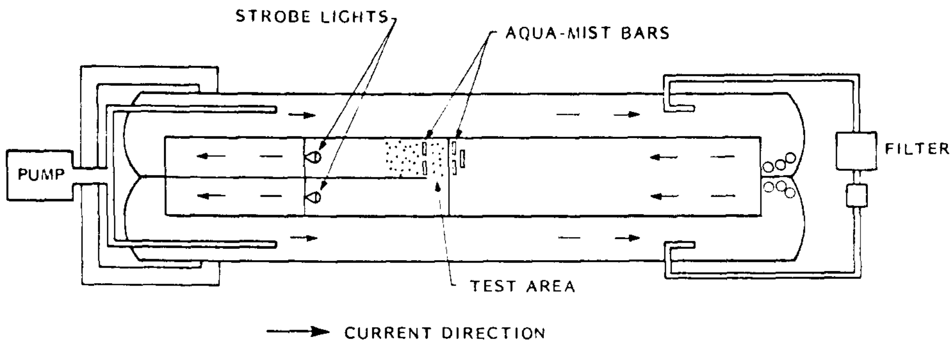

Fig. 1. Experimental avoidance behavior tank. The test area was monitored by a closed-circuit TV camera above the strobe lights. The arrows indicate the direction of water flow.

haden (*Brevoortia tyrannus*) were the species selected to assess the effects of strobe lights on their behavior under the following variables:
(1) three water flow rates (0.2, 0.3 and 0.5 m s^{-1});
(2) three strobe flash frequencies (120, 300 and 600 flashes min^{-1});
(3) two water flow rates (0.2 and 0.5 m s^{-1}) and four strobe flash frequencies (0, 120, 300 and 600 flashes min^{-1}) in combination with a bubble curtain;
(4) light and dark acclimated conditions.

METHODS

White perch, spot and menhaden were collected from the Choptank River on the eastern shore of the Chesapeake Bay, U.S.A. The specimens ranged in standard length from 85 to 237 mm for white perch, from 73 to 165 mm for spot and from 94 to 196 mm for menhaden.

A behavioral experimental tank (Fig. 1; 9 m long×2.5 m wide×1 m high) that could deliver water at regulated flow rates was used to determine fish reactions. Diffusers and baffles were used to promote an eveness of flow.

A test area within the chamber was established with the use of plastic mesh screens. The test area (1.8 long×1.2 m wide) was divided into equal-sized right and left channels by a solid partition set parallel to the direction of water flow, extending from the downstream barrier to within 25 cm of the upstream barrier. Tandy Xenon strobe lights in waterproof containers were mounted in the water column of each channel (Fig. 1). The strobe lights could be individually controlled and operated at various flash frequencies. A remote-controlled Javelin low light level camera with a zoom lens and a Sony Betamax video-cassette recorder enabled the recording of all tests for later analysis.

Two acclimation rooms for test specimens were on a 12-h day: 12-h night (red light) cycle, with the rooms 12 h out of synchronization so that specimens acclimated to light and dark were always available for testing. Since the camera and video-recorder could not be used in total darkness, the dark-adapted fish were actually acclimated to red light. The 40-watt red flourescent lights used 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 found in fish (Ali and Antcil, 1976; Levine and MacNichol, 1979). Therefore, the fish would perceive much less light with this system than with the white lights used in the other tests. Light intensities in the test area of the experimental chamber averaged 0.8 μE m^{-2} s^{-1} for white light and 0.14 μE m^{-2} 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. Specimens were held for a minimum of 3 days to acclimate to photoperiod and captivity conditions prior to testing.

Fish were tested in groups of five to account for schooling behavior. The fish were allowed 20 min to acclimate to the test area of the chamber. After the acclimation period, water flow was adjusted to the desired velocity and the distribution of the fish within the test area was recorded for 1 h. The strobe light was then lit in one of the channels of the test area and the distribution of the fish was recorded for another hour. Due to the less efficient swimming characteristics of white perch, all tests on this species used 0.5 h in each experimental period (0.5 h exposed only to the water flow and 0.5 h to the water flow and strobe light). The positions of specimens in the test area were recorded at 5-min intervals (2.5 min for white perch), the distribution observed prior to strobe-light initiation was used as the expected distribution of the fish and was compared (χ^2 test) with the distribution found after the strobe light was lit. Avoidance behavior was exhibited if a decreased usage of the channel lit by strobe light was found. Four replicate tests were run under all conditions with the strobe lit in opposite channels for one-half of the replicates to take into account any area of the chamber that may have been preferred by the fish. Initial plotting of preliminary data indicated that the χ^2 analysis was the best statistical test for the data. The χ^2 analysis was also used to provide a direct comparison of strobe light avoidance on a group of fish under a combination of influences (current, light conditions, strobe flash frequency). All statistical analyses used a significance level of $P < 0.05$.

General avoidance behavior was quantified as a percentage comparison of decreased usage of the strobe-lit channel in the experimental tank from the expected (baseline) distribution to the observed (test) distribution. The formula used was

(No. expected − No. observed/No. expected) 100%

TABLE I

Percentage reduction in usage of the strobe-lit area of the test chambers by white perch (*Morone americana*) at different water flow rates, strobe flicker frequencies and light acclimations using (A) strobe lights alone, and (B) strobe light/bubble-curtain combinations[1]

Flow rate ($m\ s^{-1}$)	Bubbles only	Flicker frequency (flashes min^{-1})		
		120	300	600
(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

[1]Negative values indicate attraction not avoidance (increase in area usage).

Avoidance was indicated if the number observed was less than the number expected.

Avoidance tests conducted with a continuous air-bubble curtain incombination with the strobe light used the same methods as described above; the only difference was that when the strobe light was lit the bubble curtain was also initiated. The bubble curtain consisted of air bubbles originating from compressed air via aqua-mist bars located on the bottom of the test chamber (Fig. 1). The mist bars were situated so the side of the test chamber to be lit by the strobe light was filled with air bubbles.

RESULTS

White perch

Strobe avoidance

White perch exhibited variable avoidance behavior under the conditions tested. White perch partially avoided strobe lights for all experiments at the 0.2 $m\ s^{-1}$ water flow rate, with a decreased use of the strobe-lit area of the experimental trough from 10 to 36% (Table IA). White perch avoidance

TABLE II

Statistical results of χ^2 analysis for avoidance behavior by three estuarine fish species to strobe lights at different water flow rates, flicker frequencies and light/dark acclimation procedures

Species	Flow rate ($m\ s^{-1}$)	Flicker frequency (flashes min^{-1})					
		120		300		600	
		Light	Dark	Light	Dark	Light	Dark
White perch,	0.2	13.0*	10.2*	25.3*	15.6*	2.7	11.7*
Morone	0.3	12.9*	5.6*	10.0*	3.2+	4.4	6.7
americana	0.5	8.5*	9.2*	6.3	9.5*	0.5+	1.4+
Spot,	0.2	8.0*	23.6*	5.7	104.7*	41.0*	64.9*
Leiostomus	0.3	21.8*+	26.4*+	13.1*	63.5*	37.3*	42.5*
xanthurus	0.5	17.5*	29.6*	8.2*	60.5*	44.3*	36.1*
Menhaden,	0.2	10.4*	14.9*	15.8*	30.8*	9.4*	38.2*
Brevoortia	0.3	23.5*+	6.3+	20.0*	3.0	8.3*	52.2*
tyrannus	0.5	1.9	5.4	14.8*	16.2*	16.0*	10.2*

*Significant at $P < 0.05$ with 3 df.
+Attraction indicated, not avoidance.

decreased at the higher water velocities. The decrease in use of the strobe-lit areas varied from 12 to 22% at 0.3 $m\ s^{-1}$ and from 8 to 24% at 0.5 $m\ s^{-1}$ (Table IA).

χ^2 analysis of the avoidance experiments indicated significant results (all analyses used $P < 0.05$) 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} (Table II) with a current of 0.2 $m\ s^{-1}$. Only light-acclimated white perch at 120 and 300 flashes min^{-1} exhibited significant avoidance at the 0.3 $m\ s^{-1}$ flow rate. The 0.5 $m\ s^{-1}$ current experiments yielded significant results for light-acclimated white perch at 120 flashes min^{-1} and dark-acclimated specimens at 300 flashes min^{-1}.

Strobe/bubble-curtain avoidance

White perch did not avoid the bubble curtain alone, but exhibited an attraction (Table IB) of 11–26% at the 0.2 $m\ s^{-1}$ water flow and 9–35% at 0.5 $m\ s^{-1}$. Experiments at 0.2 $m\ s^{-1}$ had avoidance rates of 7–58%, at all strobe/bubble-curtain combinations. The experiments at 0.5 $m\ s^{-1}$ gave mixed results with zero or low (3–6) percentage avoidance.

χ^2 analysis of the strobe/bubble-curtain combination had significant results at the 0.2 $m\ s^{-1}$ current for all conditions, except for light-acclimated specimens at 600 flashes min^{-1} (Table III). Significant avoidance results were obtained for strobe/bubble-curtain combinations, while significant attraction was found for the bubble curtain alone (at 0.2 $m\ s^{-1}$ flows).

TABLE III

Statistical results of χ^2 analysis for avoidance behavior by three estuarine fish species to strobe light/ bubble-curtain combinations at different water flow rates, flicker frequencies and light/dark acclimation procedures

Species	Flow rate ($m\ s^{-1}$)	Bubbles only		Flicker frequency (flashes min^{-1})					
		Light	Dark	120		300		600	
				Light	Dark	Light	Dark	Light	Dark
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*

*Significant at $P<0.05$ with 3 df.
$^{+}$Attraction indicated, not avoidance.

Spot

Strobe avoidance

Spot exhibited avoidance under all conditions at the 0.2 m s^{-1} current, with decreases from 9 to 100% (Table IVA). Spot had avoidance at the 0.3 m s^{-1} flow rate for 300 and 600 flashes min^{-1}, with decreases of 20–69%, but exhibited attraction for 120 flashes min^{-1} (19–22% increase). Avoidance was exhibited under all conditions at the 0.5 m s^{-1} flow, with decreases of 8–60%. χ^2 analyses of spot experiments had significant avoidance results for all conditions (Table II), except for the 120 flashes min^{-1} condition at the 0.3 m s^{-1} current, when significant attraction occurred.

Strobe/bubble-curtain avoidance

Spot gave inconsistent results for experiments using bubble curtains alone, with changes ranging from a 10% decrease to an 8–19% increase (Table IVB). Spot avoided all strobe/bubble-curtain combinations at the 0.2 m s^{-1} flow, with 21–85% decreases. Spot avoided most strobe/bubble-curtain combinations at the 0.5 m s^{-1} current (24–46% decrease), except for dark-acclimated specimens at 120 flashes min^{-1} (6% increase) and 600 flashes min^{-1} (15% increase).

χ^2 analyses had significant avoidance results under all conditions at the 0.2 m s^{-1} water velocity, except for experiments with only a bubble curtain (Table III). The strobe light/bubble-curtain experiments had significant avoidance

TABLE IV

Percentage reduction in usage of the strobe-lit area of the test chamber by spot (*Leiostomus xanthurus*) at different water flow rates, strobe flicker frequencies and light acclimations using (A) strobe lights alone, and (B) strobe light/bubble-curtain combinations[1]

Flow rate ($m\ s^{-1}$)	Bubbles only	Flicker frequency (flashes min^{-1})		
		120	300	600
(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

[1]Negative values indicate attraction not avoidance (increase in area usage).

results at the 0.5 $m\ s^{-1}$ current, except for dark-acclimated specimens at 120 and 600 flashes min^{-1} and for experiments with only the bubble curtain.

Menhaden

Strobe avoidance

Menhaden exhibited consistent avoidance of strobe light under all conditions tested. Decreases ranged from 9 to 68%, with most values near 20% (Table VA). The only major exception took place for 120 flashes min^{-1} at the 0.3 $m\ s^{-1}$ current, where attraction (7–53%) rather than avoidance was indicated.

χ^2 analyses of the menhaden experiments had significant results for all conditons at the 0.2 $m\ s^{-1}$ water flow (Table II). Significant results were obtained for all light-acclimated specimens and for dark-acclimated specimens at 600 flashes min^{-1} at the 0.3 $m\ s^{-1}$ current. Significant results were obtained at the 0.5 $m\ s^{-1}$ flow for specimens at 300 and 600 flashes min^{-1}.

Strobe/bubble-curtain avoidance

Menhaden exhibited avoidance of bubble curtains and strobe/bubble-curtain combinations under all conditions at the 0.2 $m\ s^{-1}$ velocity (Table VB)

TABLE V

Percentage reduction in usage of the strobe-lit area of the test chambers by Atlantic menhaden (*Brevoortia tyrannus*) at different water flow rates, strobe flicker frequencies and light acclimations using (A) strobe lights alone, and (B) strobe light/bubble-curtain combinations[1]

Flow rate ($m\ s^{-1}$)	Bubbles only	Flicker frequency (flashes min^{-1})		
		120	300	600
(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

[1]Negative values indicate attraction not avoidance (increase in area usage).

with changes of 9–81%. Menhaden avoided bubble curtains and strobe/bubble-curtain combinations at the 0.5 $m\ s^{-1}$ flow rate under all conditions (9–51% decrease) except for light-acclimated specimens with the bubble curtain alone.

Significant χ^2 results were obtained for menhaden under all conditions at the 0.2 $m\ s^{-1}$ water current (Table III) except for dark-acclimated specimens with 0 and 120 flashes min^{-1}. Significant results were obtained for the experiments at 0.5 $m\ s^{-1}$ with 300 and 600 flashes min^{-1} and for dark-acclimated specimens with only the bubble curtain.

DISCUSSION

Avoidance of strobe light

Phylogentically 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, as compared to other fish species in the Chesapeake Bay region. While each is a schooling species, menhaden are planktivorous and pelagic in their 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,1928).

Each species tested exhibited avoidance behavior to strobe light. Although avoidance occurred, the reasons or mechanisms are not fully understood (Patrick et al., 1985). 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. However, little information is available on the visual systems of estuarine fish. Menhaden have single and paired cone visual systems with three cone types with wavelengths of maximum absorption (λ_{max}) of 462, 517 and 566 nm (Levine and MacNichol, 1979). White perch have a visual system most sensitive at 520 nm (Wald, 1941). Spot have a λ_{max} of 499 nm (Beatty, 1973; Ali and Wagner, 1975). It is possible that the rod/cone ratio may be the controlling factor in the critical flicker fusion 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 ratio in estuarine teleost and none on the species of this study.

The species examined exhibited varying degrees of avoidance behavior, as illustrated by χ^2 analysis results in Table II. Avoidance rates decreased with increasing water flow rates. Avoidance for white perch, as a decrease in the use of the strobe-lit area of the experimental chamber, varied from 12 to 36% at the 0.2 m s^{-1} flow rate, from 12 to 22% at 0.3 m s^{-1} and from 8 to 24% at 0.5 m s^{-1} (Table IA). Of the three species tested, white perch were least capable of maintaining position in water currents. The experiments on this species had to be shortened (see Methods) because of the swimming performance of the species.

Spot were able to maintain their position at the water velocities tested, but exhibited some difficulty at higher flow rates. There was a small decrease in avoidance with increasing flow rates (Table IVA). Spot avoidance ranged from 9 to 100% at the 0.2 m s^{-1} current, from 12 to 69% at 0.3 m s^{-1} and from 3 to 55% at 0.5 m s^{-1}.

No general decrease in avoidance was indicated by menhaden as a response to water velocity (Table VA). Menhaden avoidance ranged from 9 to 22% at the 0.2 m s^{-1} water flow rate, from 8 to 68% at 0.3 m s^{-1} and from 11 to 37% at 0.5 m s^{-1}. The pelagic lifestyle of menhaden, with the attendant body form (streamlining) and swimming ability, enabled this species to maintain position in the water at all flow rates. Other species do not have the swimming ability of menhaden and are more responsive to currents, even under the influence of strobe lights. Patrick et al. (1985) found gizzard shad (*Dorosoma cepedianum*) avoidance to strobe light decreased with increasing water flow rates, with significantly ($P < 0.01$) lower avoidance at a 0.32 m s^{-1} flow than at flow rates ranging from 0.15 to 0.26 m s^{-1}.

The species tested reacted to strobe light under both light and dark conditions. Avoidance by dark-acclimated specimens was usually equal to or greater than that of light-acclimated specimens for white perch and menhaden (Tables IA and VA, respectively). Dark-acclimated spot exhibited slightly greater avoidance than light-acclimated specimens (Table IVA) under most conditions, representing an important improvement over other behavioral systems. A major constraint of behavioral systems has been that many of them 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). Although the experiments in this study were conducted in clear water, avoidance of strobe lights has been found to occur under turbid conditions. Patrick et al. (1985) found high avoidance (over 90%) for alewife (*Alosa pseudoharengus*) in turbid freshwaters, but increases in turbidity slightly lowered avoidance rates. McIninch and Hocutt (1987) found avoidance rates by the estuarine species used in this study to be equal or greater under turbid conditions as in clear water. The results of the studies using turbid waters and this study indicate that a strobe light system would be effective under low light and/or turbid conditions.

Illumination is not the only difficulty. Hadderingh (1982) illuminated the intake area of an electric 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 flourescent) used in flashing systems have not generated as consistent or as intense an avoidance reaction as strobe light (Fields and Finger, 1956; Patrick, 1982a, 1983). Fields and Finger (1956) found young silver salmon (*Oncorhynchus kisutch*) were guided more effectively by constant light than flashing light barriers. Patrick (1982a, 1983) determined that alewife (*Alosa pseudoharengus*) and gizzard shad avoid strobe light systems to a much greater extent than flashing incandescent or metal halide light systems. Obtaining avoidance behavior throughout the conditons of a 24-h cycle makes the strobe-light system more practical for application as a guidance system.

The flash rate of the strobe influences the effectivenes of the strobe-light system. Avoidance was usually higher for flash rates greater than 120 min^{-1} (Tables IA, IVA and VA). The 120 min^{-1} flash rate was the only flash frequency to have an attraction or lack of avoidance in experiments with strobe light. Both spot (Table IVA) and menhaden (Table VA) exhibited slight attraction at the 120 min^{-1} flash rate. From the χ^2 results (Table II), it can be seen that for spot and menhaden significant avoidance was more common at the 300 and 600 min^{-1} flash rates. Patrick (1982b) found avoidance to strobe light increased at flash rates over 200 min^{-1} for species tested in freshwater systems. It is possible that the slower flash rates allow fish to move through the test chamber without encountering sufficient stimuli from the strobe light to generate a sustained avoidance reaction, or that fish are able to adjust to the slow flash rate, resulting in an inconsistent avoidance reaction. Avoidance reactions at 600 flashes min^{-1} were often slightly lower than those at the 300 min^{-1} rate (Tables IA, IVA and VA). The differences between the 300 and 600 min^{-1} flash rates were less than those observed in comparison to the 120 min^{-1} rate. 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 currents, strobe flash frequency and fish species examined influence the degree of avoidance exhibited. Avoidance was greatest for all species at the lower flow rates (0.2 and 0.3 m s^{-1}) with a strobe flash frequency of 300 min^{-1}. The results indicate that site-specific considerations must be used to establish the best strobe-light system to guide fish.

Avoidance of strobe/bubble-curtain combinations

As predicted from earlier studies (Zweiacker et al., 1977; Lieberman and Muessig, 1978; Patrick et al., 1985), the bubble curtain alone did not elicit consistent avoidance behavior. Spot (Table IVB) and white perch (Table IB) were slightly attracted to the bubble barrier. Menhaden (Table VB) exhibited avoidance of the bubble curtain, but less than when combined with strobe light. Stupka and Sharma (1977) reported that air-bubble curtains were ineffective in keeping fish out of the intake of the Surry Power Station on the James River, Virginia, U.S.A. Bibko et al. (1974) established that illuminated bubble curtains were effective in guiding gizzard shad and striped bass (*Morone saxatilis*). Patrick et al. (1985) showed that gizzard shad avoided bubble curtains, except under dark conditions. Gizzard shad and menhaden are both clupeids. Their similarity in life-styles and habits, and their phylogenetic relationship, may explain their similar reaction to bubble curtains. Patrick et al. (1985) found that diversion devices (e.g. bubble barriers) illuminated by strobe light elicited increased avoidance behavior by freshwater fish over non-illuminated barriers in clear and turbid waters.

The water flow rate influenced the avoidance rate of each species. White perch (Table IB) exhibited an attraction to the bubble curtain alone at the 0.2 m s^{-1} water flow rate (11–26%) and also at 0.5 m s^{-1} (9–35%). These results are different to the avoidance of bubble curtains found by Bibko et al. (1974) for striped bass, a close relative of white perch. However, Lieberman and Muessig (1978) stated that an air curtain was ineffective in reducing impingement of both white perch and striped bass at a power plant on the Hudson River, New York, U.S.A. When strobe lights were combined with the bubble curtain, higher avoidance (9–58%) was exhibited at the 0.2 m s^{-1} flow rate than at the 0.5 m s^{-1} (3–6%) flow rate (Table IB). White perch had significant avoidance at the 0.2 m s^{-1} flow, but no significant avoidance at 0.5 m s^{-1} (Table III).

Spot were less influenced by flow rates than white perch. Spot were inconsistent, exhibiting slight avoidance (10%) or attraction (8–19%) to the bubble curtain alone at either flow rate (Table IVB). Spot exhibited significant avoidance (21–85% at the 0.2 m s^{-1} flow rate and 24–46% at 0.5 m s^{-1}; Table III) to the strobe light/bubble-curtain combinations.

Avoidance responses of menhaden were least affected by flow rates. Menhaden usually avoided the bubble curtain by 0–28% (Table VB). Menhaden exhibited avoidance of 18–81% at 0.2 m s^{-1} flow and 9–51% at 0.5 m s^{-1} for strobe/bubble combinations. Menhaden exhibited avoidance under all conditions and had their highest significant χ^2 results (Table III) at strobe flash rates of 300 and 600 min^{-1}.

Light- and dark-acclimated specimens, for all species, exhibited avoidance behavior to strobe light/bubble-curtain combinations. Avoidance was often slightly greater for dark-acclimated specimens (Tables IB, IVB and VB) for each species. Since behavioral systems are often less effective during low-light periods, it is important to have a barrier system that is effective under these conditions. Patrick et al. (1985) reported that bubble curtains were less effective in excluding alewife and gizzard shad from selected areas in the absence of light. Zweiacker et al. (1977) found similar results for other freshwater fish at a power-plant intake system.

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, but less ambiguous (Tables IB, IIB and VB). The bubble curtain elicited little or no avoidance reaction, but higher avoidance occurred at 120 flashes min^{-1}. Avoidance was generally greatest at 300 flashes min^{-1} and slightly less for 600 min^{-1}. The decrease in avoidance from the 300 to the 600 min^{-1} rate was clearer in combination experiments than in experiments on strobe light alone.

The decrease in avoidance at the highest flash rate might be the result of the fish perceiving the strobe as an almost constant light source, rendering the strobe ineffective. The high flash rate may be near the critical fusion frequency (CFF) for the visual systems of the fish. The CFF 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 CFF varies among species, at different water temperatures and at different light intensities (Hanyu and Ali, 1963, 1964). Hanyu and Ali (1964) found CFF for goldfish (*Carassius auratus*) to be at 9 flashes s^{-1} (540 flashes min^{-1}). Although exact data for the species of this study do not exist, it is probable that the flash rates reach a point of diminishing return with increasing flash rates.

For each species, the combination of strobe light with a bubble curtain did not reduce the avoidance rates, under most experimental conditions. At the 0.2 m s^{-1} water flow rate, avoidance was equal or greater for the combination experiments. The combination system was generally more effective than either the strobe light or bubble curtain individually.

At flash rates of 300 min^{-1} or greater, spot avoidance was similar for both the strobe light (9–100%) and strobe light/bubble-curtain (56–85%) systems at the 0.2 m s^{-1}flow (Table IV). At $\geq$300 flashes min^{-1}, white perch exhibited a slight increase in avoidance for the combination system (7–58%) as compared to strobe lights alone (10–36%) in a current of 0.2 m s^{-1} (Table I). Menhaden showed the greatest increase in avoidance from the strobe light (9–22%) to the combination (34–81%) experiments (Table V) at 0.2 m s^{-1}. Menhaden exhibited an increase in avoidance at the 0.5 m s^{-1} flow rate for both the strobe (11–37%) and combination (19–51%) tests at flash rates $\geq$300 min.

The greater reaction of menhaden to strobe light/bubble-curtain combinations than that exhibited by spot and white perch is similar to species-specific reactions reported by other researchers. Stewart (1981) found that "roundfish" (saithe, *Pollachius virens*; pollack, *Pollachius pollachius*; cuckoo wrasse, (*Labrus mixtus*) responded more to bubble-curtains than "flatfish" (plaice, *Platessa platessa*; lemon sole, *Microstomus kitt*; common dab, *Limanda limanda*) in marine species. Bibko et al. (1974) found gizzard shad and striped bass avoided illuminated bubble barriers, but Lieberman and Muessig (1978) stated that a bubble curtain alone was ineffective in reducing impingement of white perch and striped bass. Demersal species (e.g. white suckers (*Catostomus commersoni*), spot and white perch) tested by Patrick et al. (1985) were often attracted to bubble barriers, while avoidance was displayed by pelagic species (e.g. alewife, gizzard shad and menhaden). Patrick et al. (1985) found the addition of a strobe light to a bubble barrier greatly increased the avoidance exhibited by pelagic species (menhaden and alewife). The use of a combination of strobe light with a bubble curtain is very promising. The combination does not reduce avoidance below levels seen for the strobe lights alone for the species tested, but increases avoidance greatly by pelagic species.

The varied response of estuarine fish to strobe light and strobe light/bubble-curtain combinations indicates that guidance systems utilizing these arrangements will have to be adjusted for the specific sites at which they would be operated. The major species to be guided, the water flow rates present and the configuration of the area would influence the design of the system. This study indicates that the best situation for a strobe light system would be employed with a bubble curtain to direct mobile species in an area with water flow rates <0.3 m s^{-1}. The adaptability and probable low construction and operation cost (when compared to other barrier devices) of a strobe light system makes it a viable concept as a fish guidance system in estuarine waters.

CONCLUSIONS

All species avoided strobe light and strobe light/bubble-curtain combinations. Only menhaden avoided bubble curtains. The estuarine species tested exhibited variations in avoidance with water flow rate, strobe flash frequency and light acclimation of the fish. Generally, avoidance was enhanced when strobe light/bubble-curtain combinations were used, especially for pelagic species.

Strobe light and strobe light/bubble-curtain combination systems show promise as guidance systems for estuarine fish. The system appears to be most effective in low-flow situations with strobe flash frequencies of 300 min^{-1} or greater.

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