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RESPONSES OF FISH TO A STROBE LIGHT/ AIR-BUBBLE BARRIER

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ABSTRACT

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The responses of selected freshwater (*Alosa pseudoharengus, Osmerus mordax, Dorosoma cepedianum*) and estuarine (*Morone americana, Leiostomus xanthurus, Brevoortia tyrannus*) species to air bubbles alone, strobe light alone, and a combined strobe light/ air-bubble barrier were investigated under laboratory conditions. Gizzard shad, alewife and smelt avoided an air-bubble barrier. Avoidance response varied with air-bubble spacing and illumination. All species tested exhibited avoidance behavior to strobe lights, which varied with current velocity, strobe flash rate, and acclimation of fish. Increased avoidance was evident for most species when strobe lights were combined with air bubbles as an exclusion barrier. A combined strobe light/ air-bubble scheme shows potential for application in fish management schemes. Strobe light is more effective than continuous light.

INTRODUCTION

The use of behavioral schemes in fish management practices has recently received considerable attention. Interest has been focused on the use of light to control the movement of fish at power-plant intakes (Hocutt, 1980). In this application, lights have exhibited potential for excluding fish at power plants (Patrick and Vascotto, 1981; Hadderingh, 1982; Patrick et al., 1982) or directing or guiding fish towards a fish bypass system which usually consists of a fish pump (Haymes et al., 1984; Rogers and Patrick, 1985; Sager et al., 1985). Lights have also been used to increase commercial fish catches (Hunter, 1968; Loesch et al., 1982) or to direct fish movements (Wickham, 1973) in open waters.

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The use of air bubbles to guide or divert fish has also been suggested in fish management (Von Brandt, 1967; Stewart, 1982). However, its application for fish exclusion at power plants has generally received mixed reviews (Hocutt, 1980). Bubble screens have been reported to be ineffective at night or under highly turbid conditions. However, a critical analysis of the literature by Ontario Hydro indicated that some previous failures were the result of poor experimental design, and consequently data were difficult to interpret. It is likely that the effectiveness of a bubble screen could be increased if it were illuminated.

The objective of this study was to determine the responses of fish to strobe light and air bubbles, both alone and in combination, as an exclusion scheme. It was felt that strobe light would be more effective than a continuous light source for repelling fish. Strobe light, which can be simply defined as intermittent high-intensity light of short duration, has been effective in repelling certain species of fish (Patrick et al., 1982). In this study, information was also provided on the influence of turbidity, current, flash rate and acclimation as affecting fish response to both strobe light and air-bubble barriers. These factors were considered important for either enhancing or reducing the effectiveness of these deterrents. The results presented summarize some of the data collected on both freshwater and estuarine species from the research laboratories of Ontario Hydro and the University of Maryland. These research studies were conducted independently.

MATERIALS AND METHODS

Species investigated

Freshwater species

Alewife (*Alosa pseudoharengus*), smelt (*Osmerus mordax*) and gizzard shad (*Dorosoma cepedianum*) were tested for avoidance behavior to either strobe light alone, bubbles alone, or a combined strobe light/air-bubble barrier. These species were selected since they comprise most of the fish impingement at Ontario Hydro's generating stations located on the Great Lakes. Adult shad, ranging in size from approximately 25 to 40 cm, were collected by electro-fishing in Lake Ontario near the Pickering Nuclear Generating Station (N.G.S.), located approximately 70 km north-east of Toronto, Ontario, Canada. Alewife and smelt were collected by beach-seining at night near Pickering N.G.S. Alewife ranged in size from approximately 11 to 16 cm (total length), whereas smelt were slightly smaller (7—10 cm total length). Fish were allowed several days to acclimate to photoperiod (14 h L; 10 h D) and test-tank conditions prior to testing.

Estuarine species

White perch (*Morone americana*), spot (*Leiostomus xanthurus*) and menhaden (*Brevoortia tyrannus*) were tested for avoidance behavior to strobe light alone and combined with air bubbles. These fish are the principal species impinged at generating facilities operated by the Potomac Electric Power Company. All specimens were collected using seines, trawls and trap nets from the Choptank River on the eastern shore of Chesapeake

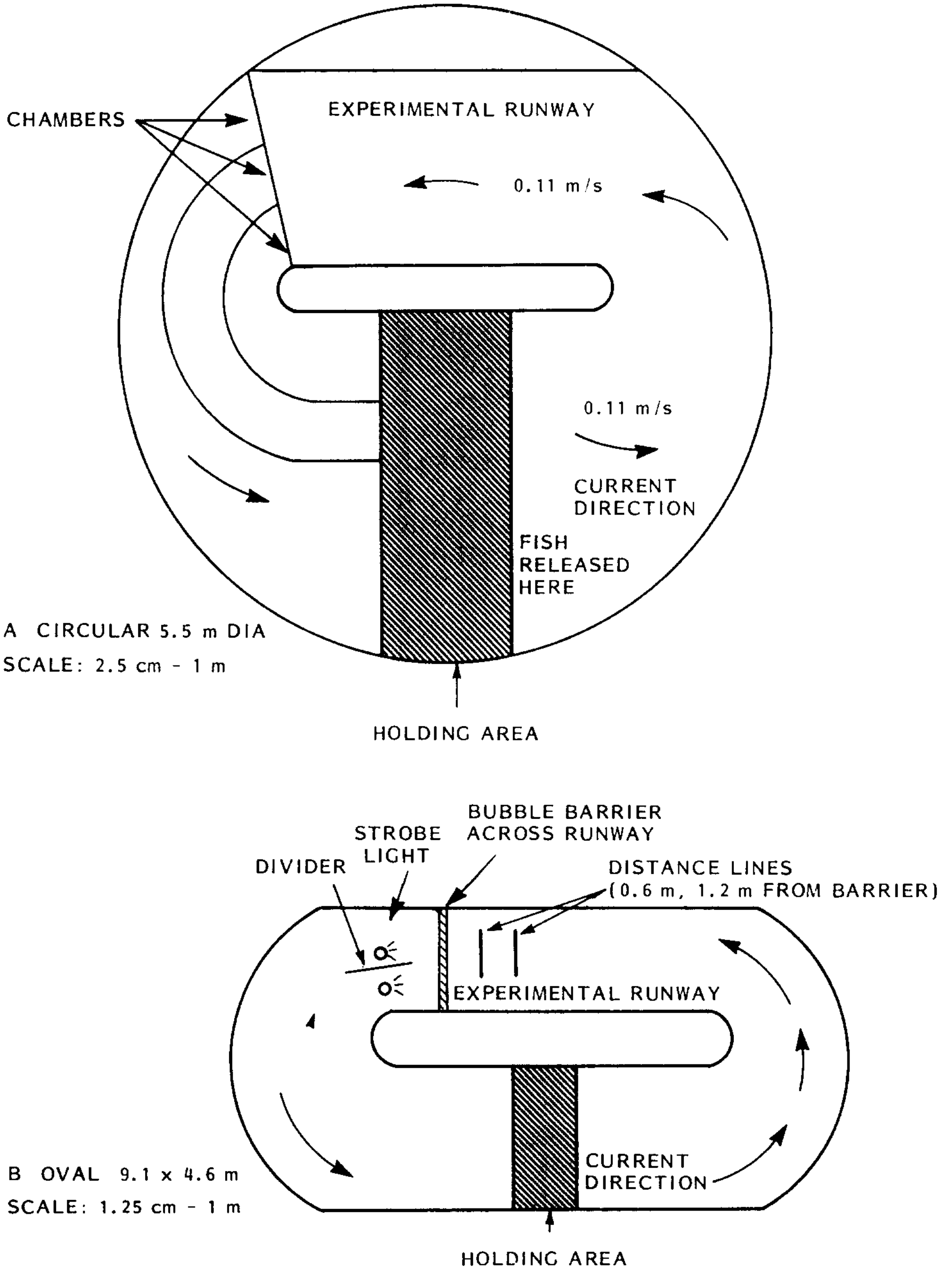


Fig. 1. Experimental facility used in tests involving freshwater species.

Bay in Maryland, U.S.A. Test species ranged in standard length from 8 to 22 cm for white perch, from 8 to 16 cm for spot, and from 13 to 20 cm for menhaden. Specimens were held for at least 3 days to acclimate to photoperiod conditions prior to testing.

Bubble wand and strobe light

Porous ABS plastic (1.0 cm I.D.; 3.0 cm O.D.) was used as the bubble wand in tests conducted on the freshwater species, and essentially consisted of a tube filled with sand. In tests conducted on the responses of fish to air bubbles alone, bubbles were spaced 0 (continuous), 5, 10 or 20 cm apart. Bubble size immediately following release was less than 1 mm in size and was consistent in all tests. In combined strobe light/bubble tests, a continuous wand was used. In tests conducted on estuarine species, the bubble curtain consisted of air bubbles originating from compressed air via aqua-mist bars located on the bottom of the tank. The bubble curtain was continuous in the combined strobe light/bubble tests. Bubble size was similar to that used in tests conducted on the freshwater species.

The strobe (xenon) light sources, which were provided by Tandy Electronics, had a flash power of approximately 1 watt and a flash duration of approximately 80 microseconds. The spectral distribution curve for the strobe was relatively uniform over the 400—700-nm range, with slightly higher energy in the blue-green regions of the visible light range.

Experimental design

Freshwater species

The initial responses of fish to bubbles of different spacing (0, 5, 10 or 20 cm) were evaluated in a 5.5-m circular pool (Fig. 1). The experimental runway was approximately 3.6 m in length and 1.5 m in width, and had a depth of approximately 1.0 m. Bubblers to be tested were placed in front of Chambers 2 and 3 where fish movement in control tests (absence of barriers) was highest. Experiments were conducted under both simulated day (0.1 μE m^{-2} s^{-1}) and night (light less than 0.01 μE m^{-2} s^{-1}) conditions. Alewife, smelt and gizzard shad were used in these tests. Fish were acclimated at least 24 h in this tank prior to testing.

For each experiment, fish (20 individuals or more) were released and directed with the current (0.11—0.12 m s^{-1}) towards the experimental runway. Responses to each bubble barrier were monitored using closed-circuit TV and by visual observation. A 1-h monitoring period was sufficient to obtain a fish behavioral response. Five replicated experiments were performed for each bubble spacing, and information was obtained on the number of fish that entered and/or passed through each barrier relative to the number of passages in the control (no barrier present) tests.

Ten controls were also conducted during day and night periods to determine fish entry into each chamber in the absence of a barrier over a 1-h time-period. To reduce temporal bias, controls were performed between experimental replicates throughout the study.

The responses of fish to strobe light as a repellent were next evaluated in a large oval pool (9.1 × 4.6 m; Fig. 1). A different group of fish were used in these tests. As in the bubble tests, fish were allowed to acclimate at least 24 h in the tank prior to testing. The experimental runway or zone was approximately 5.0 m in length and 1.5 m in width. Tests were conducted with gizzard shad. Strobe flash-frequency was at least 300 flashes min^{-1}. Light intensities, measured as quantum flux, ranged from approximately 0.6 $\mu\text{E m}^{-2}\ \text{s}^{-1}$ 0.6 m from the source to approximately 0.1 $\mu\text{E m}^{-2}\ \text{s}^{-1}$ 2.4 m from the source. At the end of the experimental runway, the light was less than 0.1 $\mu\text{E m}^{-2}\ \text{s}^{-1}$. Current velocities of 0.15, 0.22, 0.26 and 0.32 m s^{-1} were used in the design and were relatively uniform in cross-sections of the experimental zone. Five replicated tests were performed, each lasting 30 min. For each replicate, fish (n=25) were released from a holding area towards the experimental zone, and their responses to strobe light were monitored using closed-circuit TV. Tests were conducted only in darkness. Information was obtained on the number of fish passages and encounters 0.6 and 1.2 m from the light source. Five control tests were also conducted for each current speed to determine fish numbers and distribution in the absence of strobe light.

Experiments designed to evaluate the effectiveness of a combined strobe light/air-bubble barrier as an exclusion scheme were also conducted in the large oval pool (Fig. 1). These experiments followed the strobe light tests and involved different groups of fish. For each test, the combined strobe light/air-bubble barrier was evaluated relative to air bubbles alone and control tests (no barrier present). The experiments were conducted in either clear or turbid (1.0 NTU; 3.0 NTU) conditions and at current velocities of approximately 0.15 and 0.32 m s^{-1}. Turbidity conditions in the pool were created by the use of fine sediment (< 2 mm) collected from the Pickering N.G.S. discharge. The sediment was distributed homogeneously throughout the tank. The bubble screen was placed 0.6 m in front of the strobe light source. Strobe flash-frequency exceeded 300 flashes min^{-1}. Light intensities ranged from approximately 0.2 $\mu\text{E m}^{-2}\ \text{s}^{-1}$, estimated on the bubble barrier, to less than 0.1 $\mu\text{E m}^{-2}\ \text{s}^{-1}$, 3.0 m from the light source, under clear water conditions. Light intensities varied inversely with turbidity. Under low turbidity conditions, light intensities ranged from approximately 0.5 $\mu\text{E m}^{-2}\ \text{s}^{-1}$ on the bubble barrier to less than 0.01 $\mu\text{E m}^{-2}\ \text{s}^{-1}$ 3.0 m from the light source. Under highly turbid conditions, irradiance estimated on the bubble screen was less than half that measured under clear conditions.

The duration of each test was 30 min. Five replicates were performed for each experimental condition (current, barrier, turbidity). Twenty-five fish were used in each test. Observations on the number of fish approaches were made 1.2 m from the barrier. Five control tests were conducted by monitoring fish movement and distribution in the experimental zone in the absence of barriers.

Data were analyzed using analysis of variance comparing the mean number of fish passages or encounters in the experimental tests relative to that found under control conditions. If the *F*-statistic was significant, cell means were compared using a Student—Neuman—Keuls multiple range test. Vertical bars in Figs. 3, 4 and 5 refer to standard deviations.

Estuarine species

The response of white perch, menhaden and spot to strobe light alone were conducted in a 7.9 m x 2.4 m rectangular tank (Fig. 2). The size of the experimental zone was approximately 1.8 m x 1.2 m. Strobe lights were mounted in water-proof containers in the water column, against the downstream screen barrier. The strobe lights were lit in opposite channels for one-half of the replicates. Strobe flash frequencies of 300 and 600 flashes min^{-1} were used. Tests were conducted at two water velocities (0.2 or 0.5 m s^{-1}) for both light- and dark-acclimated fish. The acclimation period was at least 3 days on a 12:12 h day:night cycle. Fish were also allowed 20 min after being introduced into the tank for acclimation to the test tank, and were further acclimated up to 60 min to each current velocity prior to testing. Observations on the number of fish passages in the strobe-lit channel were made using closed-circuit TV and by visual observation over a 1-h monitoring period. Day and night simulated tests were conducted. Since the video equipment could not be used in total darkness, a red light source (40 watts) was introduced to enable use of the camera system. The red fluorescent lights used had a peak wavelength of 630 nm, with 98% of light between 600 and 750 nm, which is near the upper limit of sensitivity found in fish. The red light had little or no influence on the fish. Light intensities in the test tank, measured as quantum flux, averaged 0.81 $\mu\text{E m}^{-2}\text{ s}^{-1}$ in the day (white) light tests. Red light intensities averaged 0.14 $\mu\text{E m}^{-2}\text{ s}^{-1}$.

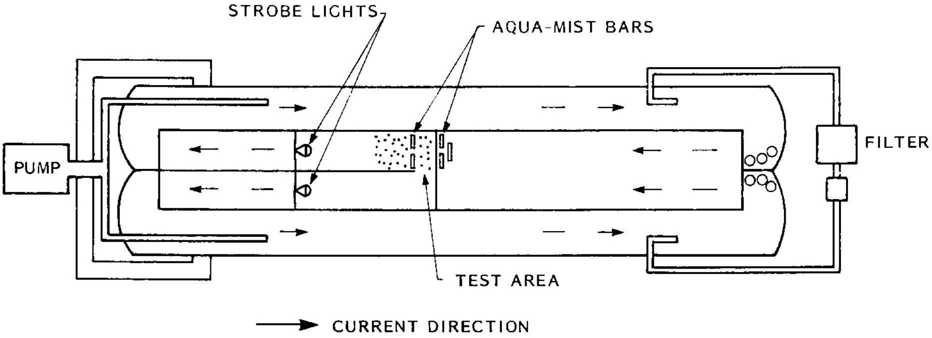


Fig. 2. Experimental facility used in tests involving estuarine species.

Four replicates were conducted for each test condition (flash rate, current velocity) for both light- and dark-acclimated fish. Five fish were used in each test.

Experiments were also conducted on the effectiveness of a combined strobe light/air-bubble scheme for excluding fish. In these tests, the same experimental procedure as described above in the strobe light alone tests was used. Air-bubble wands were placed approximately 1.2 m in front of the strobe light sources. Tests were conducted for both light- and dark-acclimated fish at a current velocity of 0.2 m s^{-1}. The strobe flash-rate used in these tests was 300 flashes min^{-1}.

Avoidance data were statistically analyzed using a χ^{-2} analysis. During the acclimation period, the number of fish found in the channel to be lit by strobe light was used as the expected distribution. This expected distribution was compared to the number of fish in the channel for the period after the strobe light was lit.

RESULTS AND DISCUSSION

Freshwater species

Responses of gizzard shad to strobe light at various currents

Gizzard shad showed a strong avoidance of the lighted runway at current velocities ranging from approximately 0.15 to 0.32 m s^{-1} (Fig. 3). There was a decrease of approximately 50% in the number of shad passages recorded in the experimental tests compared to the controls ($P<0.01$). The number of shad recorded 0.6 and 1.2 m from the barrier was reduced approximately 64 and 54%, respectively, compared to encounters in the control tests. Results also showed that the number of shad passages and encounters varied with current ($P<0.01$). A multiple range test indicated that mean passages in the experimental tests were highest at the 0.32 m s^{-1} current velocity, suggesting that the avoidance of strobe light may be lessened under higher current velocities.

Responses of alewife, smelt and gizzard shad to air bubbles

Air bubbles were effective in excluding all species tested, averaging approximately 98% for shad, 70% for alewife and 92% for smelt under low-level light (Fig. 4). In the night simulated tests, effectiveness was considerably lower, averaging approximately 80% for shad and 51% for alewife. For shad and alewife, spacing of air bubbles significantly influenced the responses of fish to the bubble system ($P<0.01$). A multiple range test suggested that the highest effectiveness occurred at bubbles spaced 5 and 20 cm apart for shad, and 0 (continuous) and 5 cm apart for smelt. In the shad low-level light tests, mean effectiveness varied less than 5% among all bubble spacings.

For alewife, effectiveness of air bubbles did not appear to be influenced by bubble spacing in the low-level light tests. In the night tests, the 20-cm spaced barrier more effectively excluded alewife passage than the 5-cm spacing ($P<0.05$). As noted above, illumination was found to significantly affect barrier performance in both shad and alewife tests ($P<0.01$). Mean effectiveness under low-level light was approximately 18 and 19% higher than under simulated dark conditions for shad and alewife, respectively. Night simulated tests were not conducted on smelt.

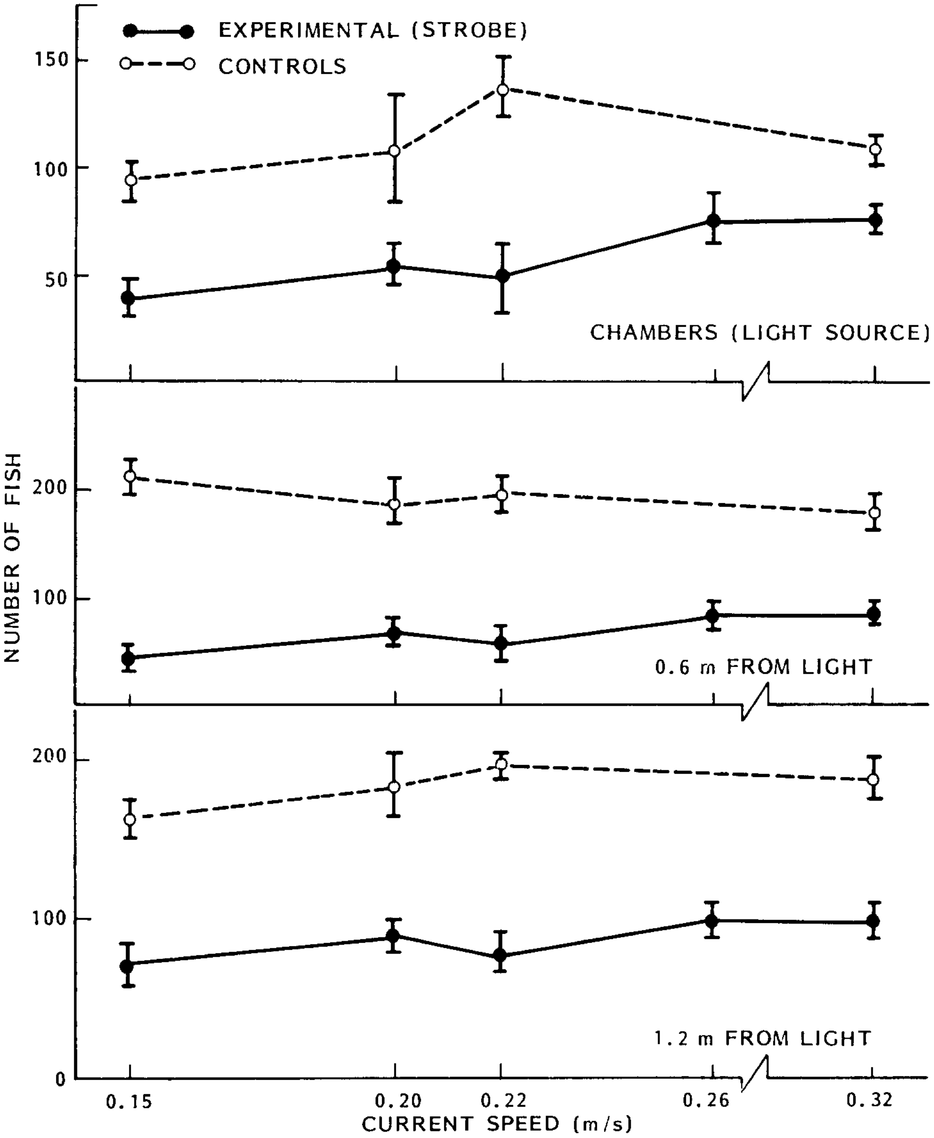


Fig. 3. Number of shad recorded in control and experimental tests at various current velocities.

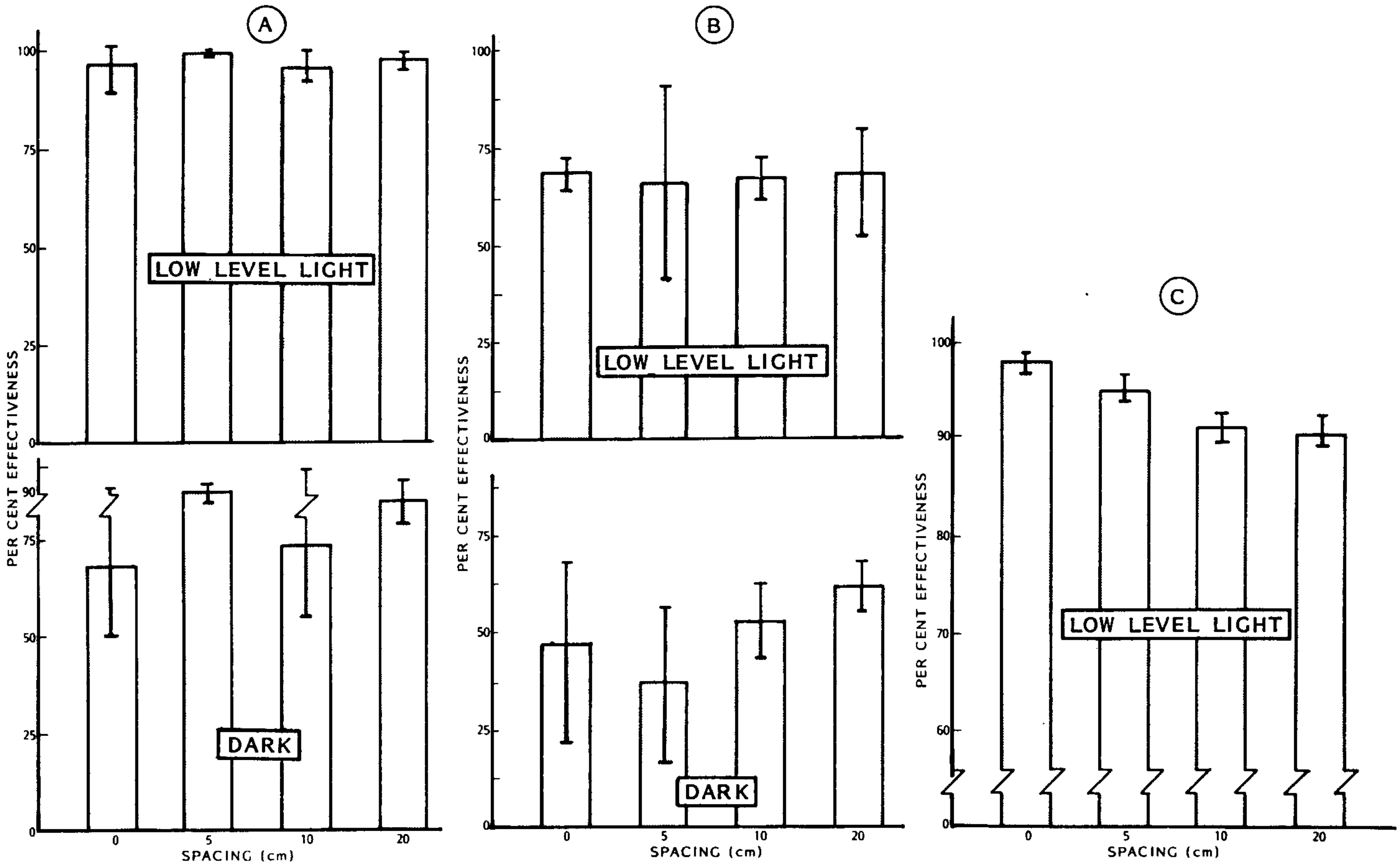
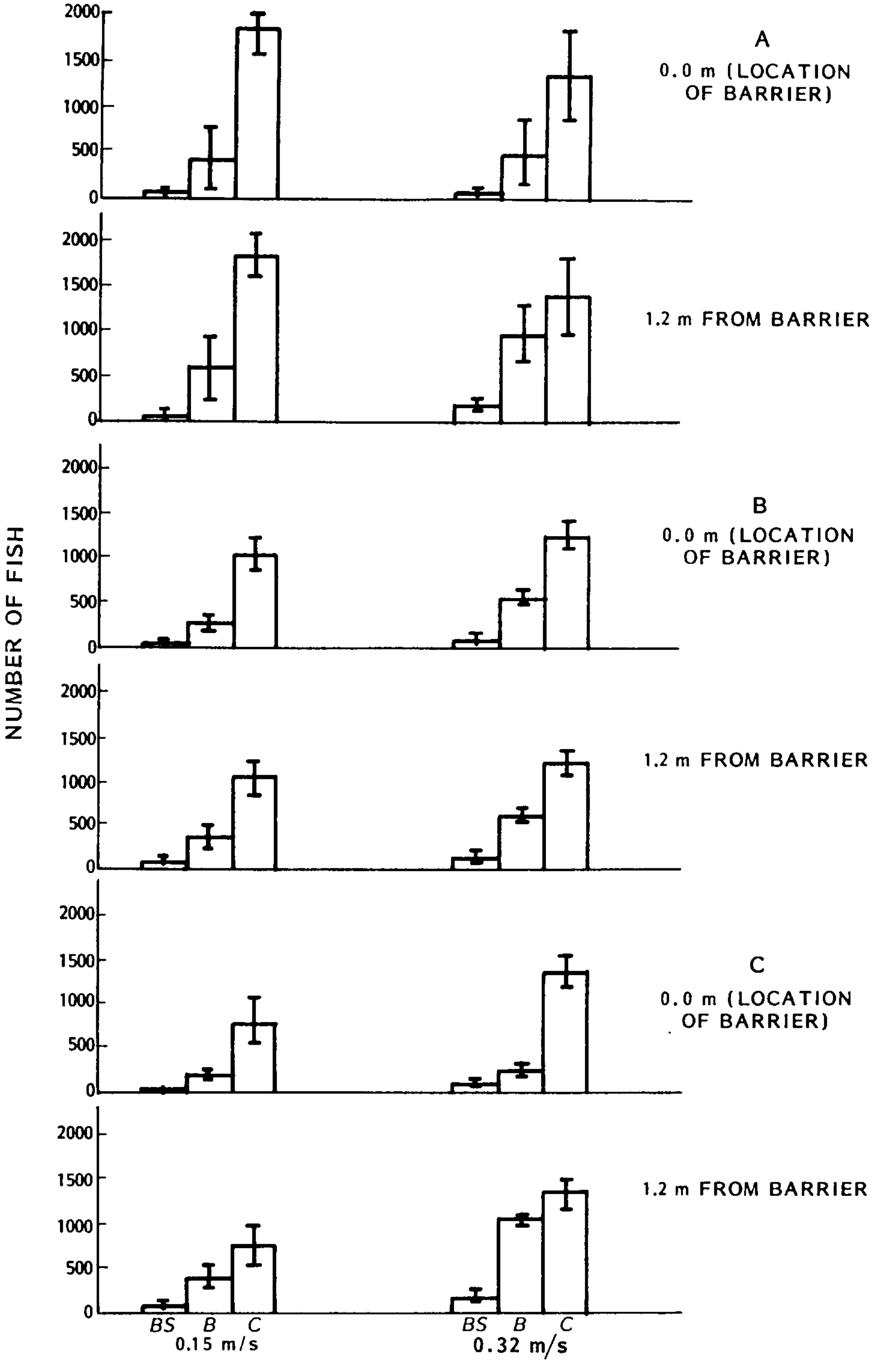


Fig. 4. Effectiveness of air bubbles in excluding: A, gizzard shad: B, alewife; C, smelt.


A
0.0 m (LOCATION OF BARRIER)
1.2 m FROM BARRIER
B
0.0 m (LOCATION OF BARRIER)
1.2 m FROM BARRIER
C
0.0 m (LOCATION OF BARRIER)
1.2 m FROM BARRIER
NUMBER OF FISH
0
500
1000
1500
2000
BS
B
C
0.15 m/s
BS
B
C
0.32 m/s

C = CONTROL

Responses of fish to a strobe light/ air-bubble scheme

The effectiveness of air bubbles alone and combined with strobe light was evaluated under different turbidity conditions and at current speeds of 0.15 and 0.32 m s^{-1} (Fig. 5). Alewife showed an avoidance response to air bubbles, especially if the bubbles were illuminated with strobe light. Effectiveness of air bubbles alone ranged from 38 to 73% over all test conditions relative to control tests. Highest reductions using bubbles alone occurred under clear (73%) and low turbidity (71%) conditions at the 0.15 m s^{-1} current speed (Fig. 5). In the high-turbidity tests, effectiveness of bubbles alone was only 59 and 38% at current velocities of 0.15 and 0.32 m s^{-1}, respectively. Effectiveness was enhanced when the bubble barrier was illuminated with strobe light. On average, a combined strobe light/air-bubble scheme ranged in effectiveness from 90 to 98% depending on current and turbidity conditions (up from 38 to 73% for bubbles alone). This increase was statistically significant ($P<0.01$).

Current and turbiditity significantly affected the number of fish passages in the experimental tests ($P<0.01$). Generally, an increase in either current velocity or turbidity resulted in an increase in fish passages.

As with the passage results, there were fewer encounters observed at the 1.2-m distance mark in the experimental tests relative to that found under control conditions. The highest reductions occurred when the air-bubble barrier was illuminated with strobe light.

Estuarine species

Responses of fish to strobe light

All three species tested (white perch, spot and menhaden) exhibited avoidance behavior to strobe lights (Table I). Highest avoidance occurred with spot, followed by menhaden and white perch. Percentage effectiveness in reducing spot passage ranged from approximately 9 to 100 depending on current velocity, flash rate and acclimation of fish (Table I). All test results for spot were significant, except at a 0.2 m s^{-1} flow rate with a strobe flash-frequency of 300 flashes min^{-1} for light-acclimated specimens. Highest avoidance (100% effectiveness) occurred for fish which were dark-acclimated at a strobe flash-rate of 600 flashes min^{-1}. Menhaden exhibited a consistent significant avoidance of strobe light under all test conditions (Table I). However, the decrease were not as great as for those shown by either spot or white perch under certain test conditions. Generally, there appeared to be little difference in effectiveness between the strobe flash rates of 300 or 600 flashes min^{-1}, but avoidance was greater under dark

Fig. 5. Effectiveness of bubbles alone (*B*) and combined strobe/air-bubble barriers (*BS*) in excluding alewife. A, clear; B, low turbidity; C, high turbidity. Bubble barrier placed 0.6 m from strobe light source.

TABLE I

Effectiveness of strobe light alone and combined with air bubbles in excluding spot, menhaden and white perch

Species	Treatment	Acclimation	Strobe flash frequency (flashes min^{-1})	Current velocity (min s^{-1})	Reduction (%)
Spot	Strobe	Light	300	0.2	9
		Dark	300	0.2	79*
		Light	600	0.2	100*
		Dark	600	0.2	73*
		Light	300	0.5	12*
		Dark	300	0.5	57*
		Light	600	0.5	44*
		Dark	600	0.5	40*
	Strobe/ air bubbles	Light	300	0.2	63*
		Dark	300	0.2	85*
Menhaden	Strobe	Light	300	0.2	17*
		Dark	300	0.2	11*
		Light	600	0.2	9*
		Dark	600	0.2	19*
		Light	300	0.5	15*
		Dark	300	0.5	37*
		Light	600	0.5	22*
		Dark	600	0.5	22*
	Strobe/ air bubbles	Light	300	0.2	67*
		Dark	300	0.2	81*
White perch	Strobe	Light	300	0.2	36*
		Dark	300	0.2	31*
		Light	600	0.2	12
		Dark	600	0.2	32*
		Light	300	0.5	9
		Dark	300	0.5	24*
		Light	600	0.5	5**
		Dark	600	0.5	3**
	Strobe/ air bubbles	Light	300	0.2	36*
		Dark	300	0.2	58*

*Significant at $P<0.05$.

**Increase (%).

conditions. Effectiveness for menhaden ranged from 9 to 37%, with highest reductions occurring for dark-acclimated fish at a current speed of 0.5 m s^{-1}. Effectiveness of strobe light as a deterrent for white perch was higher at the lowest current velocity, where effectivenesss ranged from approximately 12 to 36% (Table I). All test results at 0.2 m s^{-1} flow rate were significant, except for light-acclimated specimens at 600 flashes min^{-1}. Only the tests on dark-acclimated specimens at a 0.5 m s^{-1} flow rate and 300 flashes min^{-1} resulted in significant avoidance. Tests conducted at 0.5 m s^{-1} current velocity with a strobe flash-rate of 600 flashes min^{-1} did not result in avoidance behavior by white perch but actually in a slight attraction. This indicates a reduction in effectiveness at higher current velocities, as previously noted for a freshwater species (gizzard shad).

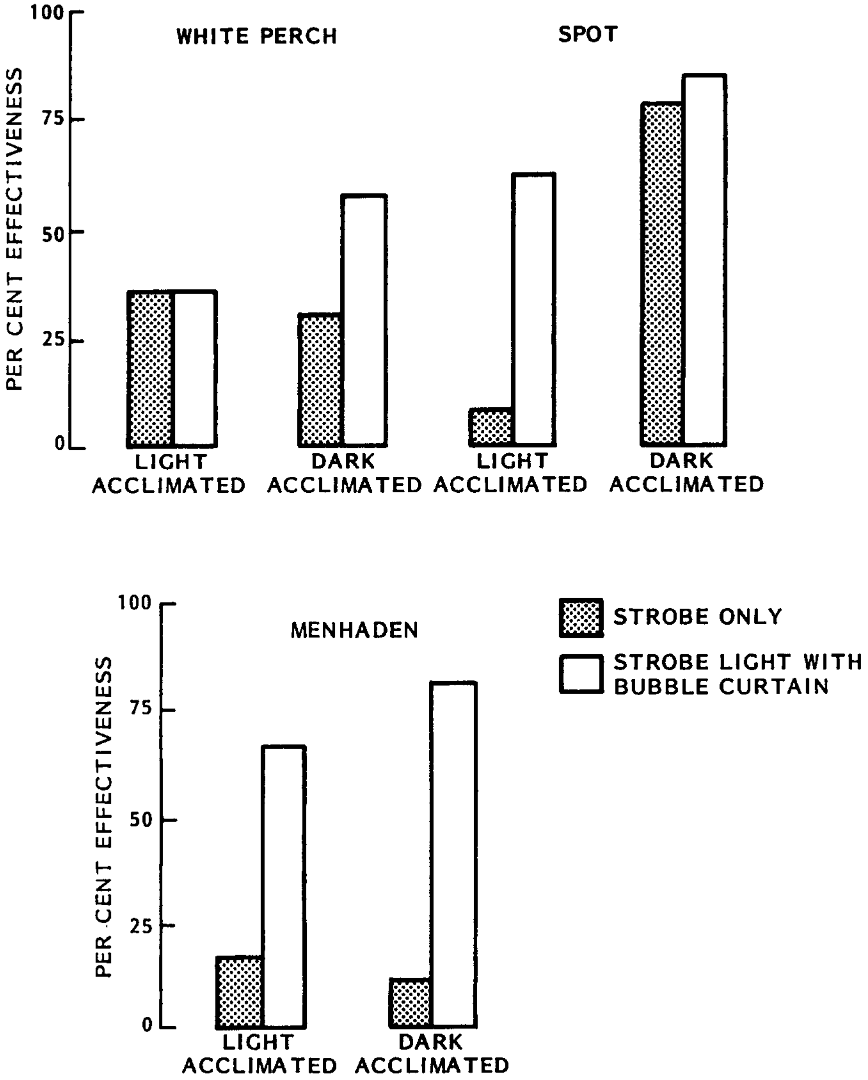


Fig. 6. Effectiveness of strobe light alone and combined with air bubbles in excluding white perch, menhaden and spot.

Responses of fish to a strobe light/air-bubble scheme

The effectiveness of strobe light alone and combined with air bubbles was evaluated for both light- and dark-acclimated fish at a current velocity of 0.2 m s^{-1} and strobe flash-frequency of 300 flashes min^{-1} (Fig. 6). All three species showed significant avoidance of the bubble barrier which was illuminated with strobe light. For spot, percentage effectiveness of this barrier system averaged 63 for light-acclimated fish and 85 for dark-acclimated specimens, which was greater than that observed using strobe light alone (Table I). There was a significant increase in effectiveness for light-acclimated fish (from 9 to 63%), whereas a smaller increase was observed for dark-acclimated fish (from 79 to 85%). Similarly, a combined strobe light/air-bubble barrier was effective in repelling menhaden, averaging 67% effectiveness for light-acclimated fish and 81% effectiveness for dark-acclimated fish. Effectivenesss of a combined strobe light/air-bubble barrier was 50% higher than observed using strobe light alone (Table I). In contrast, there was no enhanced avoidance of a strobe-lighted bubble barrier for light-acclimated white perch, although there was enhanced avoidance for dark-acclimated white perch. Percentage effectiveness of a strobe light/bubble scheme averaged 36 for light-acclimated fish and 58 for dark-acclimated specimens. In the white perch tests, it was observed that fish would readily penetrate the bubble barrier, possibly indicating that it would not be an effective barrier to white perch movement.

Interpretive analysis

In tests conducted on freshwater pelagic species (alewife, smelt, gizzard shad), bubble spacing was an important variable affecting the performance of a bubble screen primarily for smelt, and to a lesser extent for shad. Highest effectiveness was generally observed at the smallest barrier spacings. Casual observations also indicated that the highest fish passages for all species tested occurred near the bottom of the screen where the least bubble turbulence was evident (especially with increased spacings). The effectiveness of a bubble screen was higher under low-level light than in darkness, irrespective of spacing, suggesting that the bubble barrier acted more as a visual cue than as a tactile stimulus (also noted by Stewart, 1982). Other factors, such as sound or pressure created by the bubble screen, may also play a role, as speculated by Kuznetsov (1971).

There is evidence to suggest that fish response to a bubble barrier alone may not be consistent for all species. Several demersal species tested,which included white suckers (*Catostomus commersoni*), spot and white perch, have been noted to be attracted to an air-bubble curtain (Patrick, 1984; Sager, 1984), which is in contrast to results with the pelagic species tested in this study (alewife, smelt and gizzard shad). Similarly, Stewart (1982) reported differences in the responses of roundfish and flatfish to a bubble barrier under low-level light. Behavioral responses to an air-bubble curtain may be significantly different for pelagic species than benthic ones. These differences in response are probably related to fish habitat/selection.

Results with gizzard shad indicated that the effectiveness of bubbles alone as a deterrent was reduced in the absence of light, suggesting that the bubble screen should be properly illuminated to obtain the maximum effectiveness under dark or highly turbid conditions (i.e. when visibility is reduced).

Both freshwater and estuarine species tested exhibited avoidance behavior to strobe light. Although avoidance occurred, the actual reasons or mechanisms are only partly known. We have evidence indicating that fish avoidance is probably related to flash-rate and duration of the flash (in micro seconds) rather than to the spectral composition of the light source. However, results of this study do indicate that strobe light alone is not as effective as a combined strobe light/air-bubble scheme in reducing fish passage. Spot avoidance increased from 9 to 63% for light-acclimated fish, and from 79 to 85% for dark-acclimated fish. Increases in effectiveness observed for menhaden were at least 50% higher when strobe light was used in association with a bubble barrier than with strobe lights alone. Similarly, for tests conducted on freshwater species (alewife), the addition of strobe light to the bubble barrier increased overall performance from 38 to 73 or 93–98%.

A combined strobe light/air-bubble scheme shows promise in fish management. Apart from possible uses for diverting fish at power plants, this system may have potential in fish harvesting (Stewart, 1982). At present, this barrier system has not been rigorously tested under field conditions. Further research is warranted.

CONCLUSIONS

Alewife, gizzard shad and smelt showed avoidance to an air-bubble barrier. Illumination and bubble spacing were found to significantly affect the barrier performance as a fish excluder.

All species tested exhibited avoidance of strobe light which varied with current velocity, flash-rate and acclimation of fish.

Generally, avoidance responses for each species was enhanced when air bubbles were combined with strobe light as an exclusion scheme. A combined strobe light/air-bubble scheme shows promise in fish management.

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