To the Graduate Council:

I am submitting herewith a thesis written by Rebecca R. Bowles entitled "Effects of Water Velocity on Activity of Juvenile Striped Bass." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Ecology.

David A. Etnier, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Vice Chancellor
Graduate Studies and Research

EFFECTS OF WATER VELOCITY ON ACTIVITY OF JUVENILE STRIPED BASS

A Thesis

Presented for the

Master of Science

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Rebecca R. Bowles

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ABSTRACT

The swimming activity of juvenile striped bass (Morone saxatilis Walbaum) 8 to 80 mm long was investigated in a test chamber simulating, on a small scale, a fixed-screen cooling water intake structure. As water velocity increased from 0 to 30 cm/sec area and distance traveled by juvenile bass 10 to 80 mm long decreased. However, as water velocity increased from 0 to 3 cm/sec area and distance covered by larval bass increased. The presence of food increased the activity of larval bass, but decreased the activity of juveniles. Area ranged by striped bass at test velocities ranging from 0 to 30 cm/sec increased in proportion to body length. Juvenile striped bass tested at acclimation temperatures between 20 and 5 C experienced a 30% reduction of activity. Activity was also reduced as temperature increased from 20 to 30 C.

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CHAPTER I

INTRODUCTION

An increasing energy demand has led to the construction and expansion of a large number of power plants. At present, steam electric power generation annually requires 227 trillion/yr (60 trillion gal/yr) or approximately 15% of the total river and stream flow in the United States (USEPA, 1973a). Interactions between aquatic organisms and power plants represent an area of growing environmental concern.

Cooling water intakes and discharges are two distinct interfaces power plants have with the aquatic ecosystem. Previous emphasis has been directed at biological damage and/or enhancement created by thermal effluents. Deficiencies in knowledge of water intake-associated biological damage have recently become apparent.

Biological damage occurring at cooling water intake structures is generally classified as entrainment, entrapment, or impingement. Aquatic organisms less than 50 mm long are not usually retained on intake screens and are subsequently entrained through power plant pumps and condensers. Entrapment occurs when fish are drawn with the cooling water flow into forebays, areas immediately in front of intake screens. Mortalities occur when plant condenser cooling lines are thermally or chemically back-flushed or

when organisms, having no route of escape, swim until exhausted and fall against the intake screen. Impingement occurs when fish are unable to escape from the surface of the intake screen.

The study of environmental aspects of cooling water intake structures requires a multidisciplinary approach. Such diverse fields as engineering, physiology, and ethology contribute to the understanding and reduction of adverse intake conditions. While important contributions from other disciplines are considered, observation of fish behavior is the basis for the following investigation.

CHAPTER II

RELATED LITERATURE

A significant percentage of fish mortality due to entrapment and impingement can be avoided by combining 1) engineering design, 2) familiarity with swimming stamina of fish at various life stages, and 3) recognition of behavioral characteristics of local fishes under a variety of physical conditions (Schuler and Larson, 1974; Bibko et al., 1974; Riesbol, 1974). Research efforts have been stimulated by the Federal Water Pollution Control Act as amended in 1972 (Public Law 92-500). In section 316(b) the act requires that "...the location, design, construction and capabity of cooling water structures reflect the best technology available for minimizing adverse environmental impact."

Intake Siting and Engineering Design

Physical location of power plants has significant impact on the magnitude of fish mortality. Cooling water sources include lakes, rivers, oceans, and estuaries. Because estuarine environments are highly productive, substantial damage to the standing crop of many organisms is likely in these locations (Landry and Strawn, 1974). Tidal action and salinity are design problems in estuarine and near-shore ocean intake structures. Lake sites present

difficulties with thermal stratification. River locations may face low flow and siltation problems (USEPA, 1973b).

Location of cooling water intakes with respect to the shoreline of a given body of water may influence the amount of biological damage (Bainbridge, 1964; Sonnichsen et al., 1973). Generally, intakes located at the head of a cove or canal attract, trap, and impinge large numbers of fish. A flush-with-shoreline design is considered best technologically because it utilizes natural currents to remove fish and debris from the intake (USEPA, 1973a).

Initially the problem of excluding fish and other debris from water intakes was viewed from an engineering point-of-view. Primary considerations were physical protection of power plant condenser cooling tubes and maintenance of constant hydraulic head (Bell, 1974). Design engineers accepted existing intake configurations as standard without consideration of site specific environmental conditions (Sonnichsen et al., 1973).

Burns (1966) described a diversity of commercial and industrial intake screen designs including revolving drum screens, link belt screens, perforated plates, and louver diverters. Several conventional screen designs were reviewed by Mayo (1974) who suggested fixed screens had on-shoreline applications where strong currents parallel to the face of the screen carried fish away from the orifice. Traveling screens of various configurations were most popular and had

widest adaptability (Bates and Vanderwalker, 1970). Filtering systems such as rapid sand and gravel or leaky dam filters were new designs but were limited by capacity. Alternative and as yet untested methods were suggested such as an in-stream heat exchanger (Mayo, 1974). Other non-screening methods for protection of aquatic life involved closed-loop cooling towers which reduced the total volume of water required.

Before development of self-cleaning traveling screens fish removal was accomplished by laborious, manual clearing and in the case of fixed screens even required plant shutdown (Kerr, 1953). Handling stress was added to impingement stress and mortalities were high. Early traveling screens were not equipped with baskets and incidents of reimpingement were frequent (Mayo, 1974). A basket system was developed for use with traveling or stationary screens. In fixed screen applications the leading edge of the basket scraped fish from the screen and deposited them in a fish removal flume. Basket-scrapper systems damaged as many fish as they saved (Landry and Strawn, 1974). Low pressure water jets were developed to gently remove impinged organisms and traveling screen velocities were increased to improve survival. Fish removal flumes were designed to be hydraulically smooth and permit rapid return of fish with minimum damage (Mayo, 1974).

Schuler (1973) suggested that an array of louvers placed in front of intake screens could be useful in diverting fish. Louvers could be variously spaced and oriented at an optimum guiding angle for a particular velocity. However, as Eicher (1974) pointed out, guiding louvers lose their efficiency in low velocities. Similar information on guidance using velocity barriers or vanes showed placement of vanes does effect the path of swimming fish (Kerr, 1953).

Another intake design, called a velocity cap, has reduced fish mortality by as much as 90% below conventional designs (Weight, 1958). A velocity cap is a concrete slab placed a short distance above the inlet of an intake pipe opening vertically a few feet above the floor of a body of water. A less abrupt change in velocity is produced by reorienting the flow pattern from vertical to horizontal. However, by creating reef-like microenvironments such intakes actually attracted fish (Downs and Meddock, 1974).

Two additional engineering problems must be considered in siting and design of power plants. Area hydraulics must be favorable and fish protection measures designed must be economically feasible. Sonnichsen, et al. (1973) pointed out that ecological necessity in design may not be economically practical. Kerr (1953) demonstrated that intake-guidance systems successful at one site were frequently unsuccessful in reducing fish mortalities at other locations. Because of site specific parameters, each fish preservation

scheme must be custom designed for a particular application. This contributes substantially to initial engineering costs.

Physiology of Swimming Fish

One of the most critical design features with respect to the magnitude of fish mortality at power plants is the approach velocity, the rate at which water travels prior to passing through the intake screen. Many techniques have been developed to measure the swimming ability of various species of fish and in some cases swim speed data have been used to avoid lethal approach velocities. Types of apparati used to study swim speed included oval channels (MacLeod, 1967), rotating circular (annular) channels (Gray, 1937; Fry and Hart, 1948; Bainbridge, 1958), and glass or steel pipe (Brett and Glass, 1973).

In an attempt to quantify the ability of a wide variety of fish to swim at a range of velocities the following types of swim speeds were defined (King, 1970; Sonnichsen *et al.*, 1972; Bibko *et al.*, 1974):

1) crusing speed - mean water velocity against which a fish could swim for hours.
2) sustained speed - maximum water velocity against which a fish could swim continuously for a test period of several minutes.
3) dart, burst, or escape speed - maximum water velocity against which a fish could swim in short bursts with some forward progress from a single effort.

Definitions of swim speeds were as varied as the experimental methods. Burst speed was quantified by Bainbridge (1958) as $V = 1/4\ L\ (3f - 4)$ where V was speed in cm/sec, L was body length in cm, and f was frequency of tail beats/sec. Maximum swim speed was defined by MacLeod (1967) as the velocity at which fish could swim for at least three minutes in a current slightly exceeding their swimming ability. Bibko et al. (1974) defined impingement velocity as that necessary to bring about impingement in 30 sec. Final swimming speed (Brett et al., 1958) was the velocity which held a fish permanently against the intake screen. Critical swim speed was defined by Hocutt (1973) as the speed at which an individual can no longer actively orient to the current.

The swimming ability of fish is closely related to metabolism. Fry (1947) observed animals have a scope for activity, the energy difference remaining once the metabolic requirement for "the organism's integration" (i.e., growth, reproduction) have been subtracted from total metabolism. Temperature and dissolved oxygen are two important variables that should be considered when evaluating the swimming ability or "scope for activity" of fish at specific power plant sites (Bell, 1973).

Because fish are poikilothermic, their body temperature reflects ambient environmental temperature. The role of water temperature in swimming performance of fish has been

measured by Fry and Hart (1948), Keenleyside and Hoar (1954), Brett et al. (1958), Beamish (1966), and Bibko et al. (1974). Swimming performance decreased whenever water temperature varied from acclimation temperature (Brett, 1963). Larimore and Duever (1963), on the other hand, found by subjecting acclimated fish to a broad spectrum of test temperatures that fish performed best at 5 C above acclimation. Beamish (1966) and Brett (1963) found cruising speeds were affected by temperature. Escape speeds showed little variation with respect to temperature.

Beamish (1964) showed fish exhibit a 60% reduction in swimming ability when dissolved oxygen (D.O.) was reduced to a third of the saturation value. Decreased oxygen effects various species differently. Swim speeds of juvenile large-mouth bass, Micropterus salmoides, were independent of dissolved oxygen above 6 mg/l at 25 C, but swim speeds were reduced when D.O. fell to 5 mg/l. Coho salmon, Oncorhynchus kisutch, lost speed if oxygen fell below 9 mg/l (Dahlberg et al., 1968).

For larval and juvenile fish, swimming endurance varies inversely as the velocity and directly with respect to size of the fish (Bainbridge, 1958; Dahlberg et al., 1968; Bibko, 1974; and Skinner, 1974). When size data was converted to body lengths, Brett (1965) found smaller fish have higher swimming speeds.

Mortality caused by entrainment may be due to shear stress, thermal shock, chemical, or pressure stress (Coutant, 1974). Impingement mortality may result from fatigue, suffocation, or injury. Prentice and Ossiander (1974) described the relationship of velocity and length of time impinged to survival. A 12 min exposure to 15 cm/sec water velocity produced no oxygen stress in salmon fry (Oncorhyncus tshawytscha), but 15 min at the same velocity produced stress in 25% of the fry. Juvenile striped bass (Morone saxatilis) survival was slightly less than 90% at 0.15 m/sec (Skinner, 1974). Impingement of young-of-year striped bass at 2.2 to 2.8 ft/sec for 5 min produced no mortality, but only 67% survived 15 min impingement at the same velocity (Bibko et al., 1974). Mortality caused by fatigue may be due to the accumulation of lactic acid in the blood upsetting the acid-base balance (Beamish, 1966). Screen-induced injury may not cause direct mortality, but probably increases susceptibility to disease and predators.

Results obtained in swim speed tests were generally not comparable. Even when the same experimental appartus and procedure was used, Skinner (1974) found performance in identically sized fish differed as much as 40% from year to year. Bainbridge (1958) found pretest exercise improved swimming performance in some fish species. Swimming ability of young salmon increased 30% when flowing water rather than static water holding facilities were used (Skinner, 1974).

Behavioral Responses in Fish

Behavioral barriers (e.g., air bubble screens, illumination, noise, velocity, and turbulence) to aid in excluding fish from water intake structures have been tested. Sonnichsen et al. (1973), Kerr (1953) and Eicher (1974) found air screens ineffective in restricting fish passage. Bibko et al. (1974) stated bubble curtains were equally effective in daylight and darkness, but only a 5 cm gap was needed to permit fish to pass. Air bubble tests conducted by Alevras (1974) on the Judson River showed apparent success in restricting fish passage, but tests were conducted during a seasonal population low.

Illumination caused both attractive and repulsive responses in fish. Landry and Strawn (1974) hypothesized power plant lights in an estuarine environment attracted fish. Stickney (1971) found juvenile herring were positively phototactic and increased light levels increased activity. Bibko, et al. (1974) observed initial withdrawal from an intensely lighted area, but fish subsequently became apathetic to the presence of light. Increased visual cueing may occur in illuminated intakes.

Sonic barriers using low frequency, high intensity sound frightened fish away at first, but fish shortly became accustomed to sonic barriers (Kerr, 1953). Bell (1973) stated that fish avoid sudden sound or movement, but ignore both if continued for long periods of time.

Velocity variations have been used successfully in guiding migrating fish species (Schuler, 1974). Unfortunately, variation in fish size, non-uniform flow patterns and other environmental variables make intake velocity gradients impractical. Hazardous, highly turbulent areas were avoided by most fish species (Kerr, 1953). Bell (1973) cited turbulence as a significant cause of injury near intakes.

Schuler (1974) observed dramatic differences in the behavior of large as opposed to small schools with respect to water velocity. Small schools of anchovies fatigued more rapidly. Evidence suggested schooling fishes such as anchovy (Schuler, 1974), golden shiner (Todd et al., 1972) and striped bass and gizzard shad (Bibko et al., 1974) have less complex behavior patterns than non-schooling species. The ability of fish to cope with velocity stress may be related to behavioral type or level of social interaction. Eicher (1974) found schooling fish react differently to barriers. In current strong enough to force the school close to a fish guidance device, some species were reluctant to pass through an area too small for a group. As the school swam in front of the diversion, fatigued individuals would finally pass through the opening.

Fish generally exhibit positive rheotaxis, or response to water flow (Fraenkel and Gunn, 1961), by orienting upstream. Kennleyside and Hoar (1954) observed migrating salmon and suggested failure of positive rheotaxis was due

to fatigue. Visual stimuli were also important in rheotaxis. Bibko, et al. (1974) showed striped bass have strong rheotactic response. In still water swimming was random, but all bass oriented upstream when flow resumed. Gray (1937) observed pseudo-rheotaxis, oreintation to the rotation of the test tank rather than orientation to water flow, in goldfish tested in various flow patterns.

CHAPTER III

STATEMENT OF THE PROBLEM

The purpose of this investigation was to study the behavior of juvenile striped bass approximately 8 to 80 mm in total length swimming at water velocities ranging from 0 to 30 cm/sec and at temperatures from 5 to 30 C. The research addressed a frustrating problem experienced by many researchers working with the effects of power plant cooling water intake structures on the aquatic ecosystem. The problem was stated by Bibko, et al. (1974) after extensive research on swim speed and intake related behavior of striped bass and gizzard shad:

> "...it would appear that screen intakes should not be as great a problem as it is...intake velocities present at most power plants (0.5 to 1.0 ft/sec) should not impinge fish such as young striped bass, which may apparently escape water velocities greater than 2.0 to 2.6 ft/sec, if they so chose. Clearly, other parameters such as water temperature and a variety of additional factors ... may modify a fish's normal swimming behavior with respect to water velocity."

Tests of stamina and swim speed (e.g., Bainbridge, 1958 and Brett, 1967) provide quantitative tolerance limits, but fail to consider qualitative behavioral effects of velocity on activity or the effect of such variations in activity on susceptibility to impingement. This study sought to go beyond stamina and swim speed tests to consider questions related to activity patterns. Also, few

observational data on young striped bass are available. Juvenile fish are an important life stage in assuring continued population success and at the same time they are highly susceptibile to entrainment and impingement.

Striped bass ("stripers" or "rockfish") are valuable sport fish which occur naturally along the east coast of the United States from the St. Lawrence River in Canada to the Tchefuncta River in Louisiana. In 1879 striped bass were introduced into the Sacramento - San Joaquin river system in California and are now found along much of the west coast. (Goodson, 1966). In the early 1950's land-locked populations were found following the impoundment of Santee-Cooper Reservoir (Stevens, 1958). Since the discovery of freshwater resident populations of this normally anadromous species, large reservoirs have been stocked by many states.

Striped bass were chosen as the experimental species not only because they are a widely distributed, valuable sport fish which state conservation agencies have expended large amounts of money and energy establishing, but M. saxatilis is also a top carnivore in the aquatic food web and large losses of carnivores due to entrainment/impingement have unknown environmental consequences. Striped bass feed on crustaceans and fish such as clupeids and an occasional game species. As a predator, striped bass have often been stocked for threadfin shad control (Goodson, 1966).

Assumptions

Five experimental assumptions were made.

1) Hatchery spawned, laboratory reared striped bass were assumed to display typical behavioral response patterns found in "wild" fish.
2) The test channel design was assumed to simulate a fixed screen intake structure.
3) The non-laminar flow caused by the circular nature of the test channel was held to closely duplicate the turbulent flow conditions typical of the near-screen area of intakes.
4) Levels of illumination necessary for observation and filming were assumed to have little effect on fish behavior.
5) The presence of a partially hidden observer was assumed to have little effect on the behavioral response of striped bass.

CHAPTER IV

METHODS AND MATERIALS

Larval Striped Bass Observations

Eight to fourteen-day old striped bass spawned from Cherokee Reservoir adults were obtained from the Tennessee Game and Fish Commission at Morristown, Tennessee. Bass were held and tested in a 120 cm diameter circular fiberglass tank when they were 8 mm (± 2 mm standard deviation) total length. The larval fish were acclimated and tested at 20 (± 2) C, a water temperature similar to that found in the larval environment. Activity was observed at water velocities of 0 and 3 cm/sec with and without food present. Food organisms were obtained by plankton tows in fish culture ponds near the laboratory. Composition of the tows varied, but rotifers and Daphnia occurred in great abundance.

Swimming activity was recorded as young striped bass moved over a numbered grid during 1-min observation periods. The activity grid was drawn on a rigid white plastic sheet that was suspended 5-centimeters below the water surface of the holding tank (Figure 1). The 30 x 30 cm grid had a total area of 900 cm^2 marked as 100 numbered 3 cm squares.

Observations consisted of voice recordings of the 1-min activity of individual fish. The recording was then transferred to paper from which the total area covered

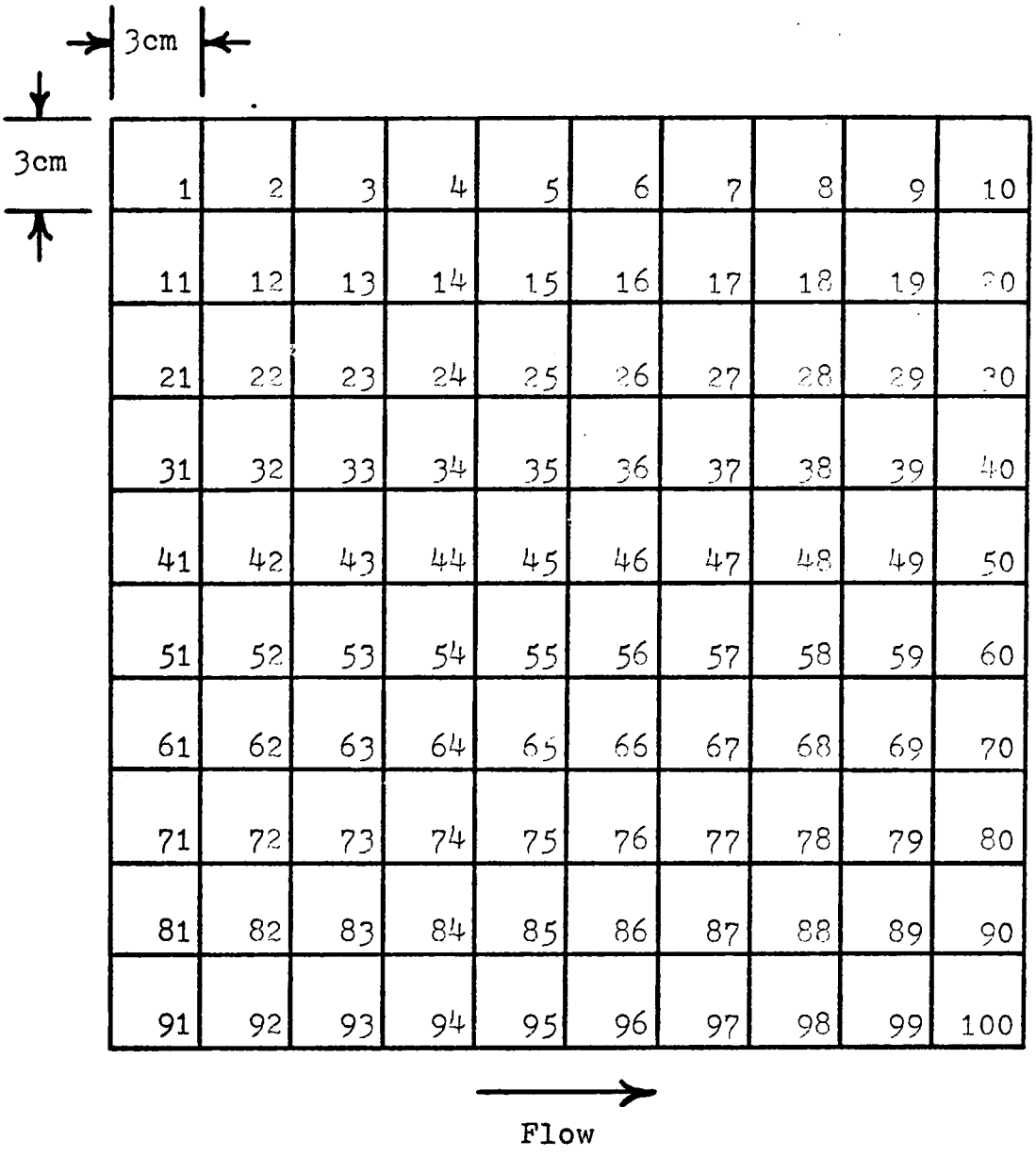

Figure 1. A numbered background grid was used to monitor the activity of larval striped bass.

during each activity period and the total distance traveled were computed. Twelve 1-min observations were made five minutes apart at two water velocities with and without food: 0 cm/sec with food, 0 cm/sec without food, 3 cm/sec with food, 3 cm/sec without food.

The following techniques were employed during recording and analysis of observational data. As the premaxillary of an observed individual crossed the border of a square the number of that square was recorded. When measurements for data analysis were made, each distance was measured from the center of one square to the center of the next square occupied. Area occupied during each movement was considered to be the total area of the square, and any square not actually occupied, but entirely enclosed by a circular swimming path was included in the area ranged by an individual.

Data were analyzed by three methods. A two-way anlaysis of variance was performed for both area and distance at the two test velocities. A plot of area vs distance was made. The mean value and standard deviation for each set of experimental conditions were determined.

Juvenile I Striped Bass Observations

Striped bass retained at the completion of larval bass observations were held at 20 ($\pm$ 2) C until the desired body length had been attained. A larger, 180 cm-diameter circular fiberglass tank was used as an observation chamber (Figure 2).

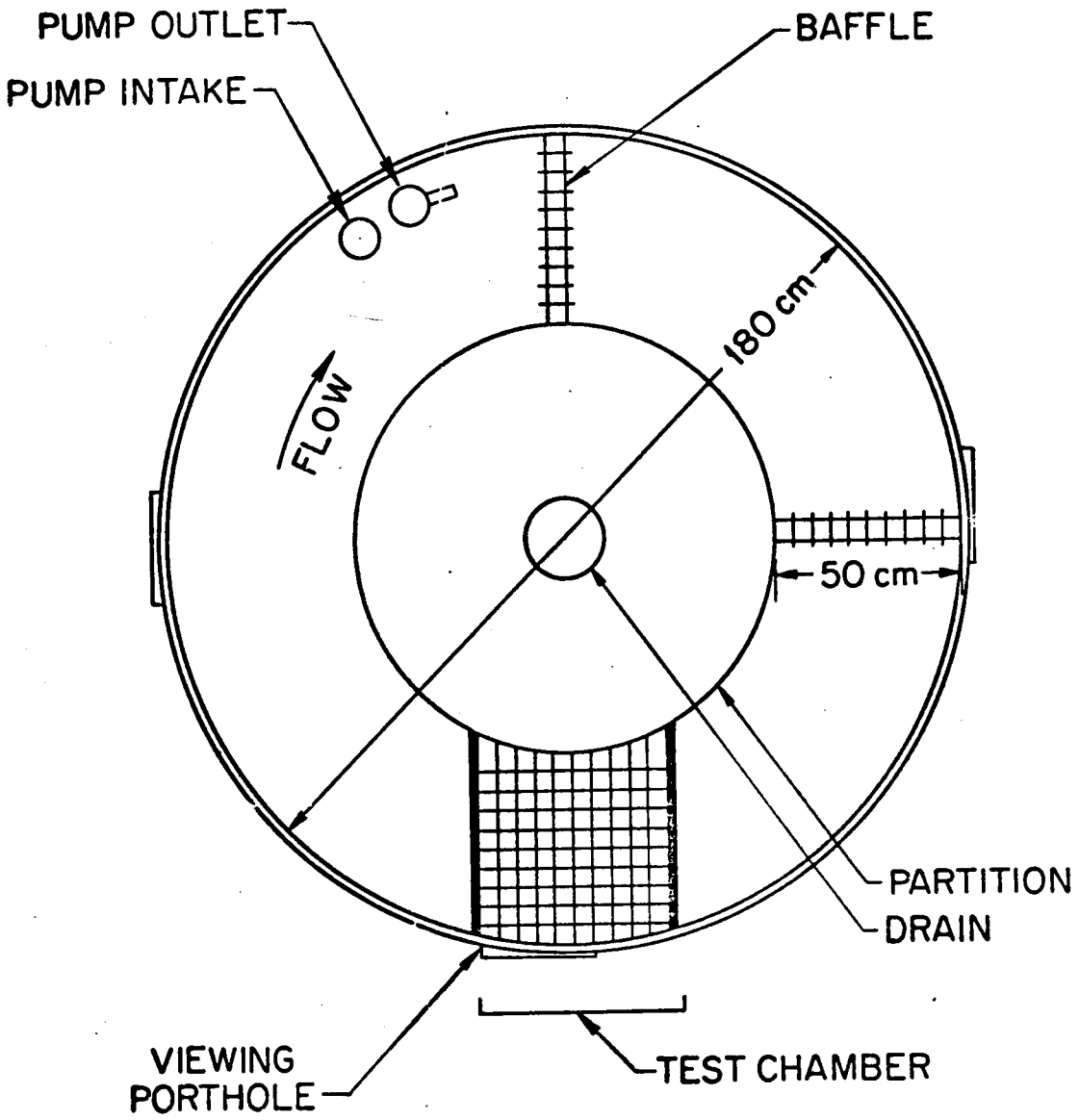

Figure 2. Tank modifications included portholes, a circular partition, baffles, and a test chamber with a numbered grid on the bottom for monitoring fish activity.

Modifications included side-view portholes, a circular partition to create a 50-cm wide by 30-cm deep channel, a series of baffles to reduce turbulence, and an application of white paint to inside surfaces to provide greater visibility. Two 2 mm mesh screens blocked the upstream and downstream ends of the 2025 cm^2 test area. A numbered grid drawn on the bottom of the test area was used to locate fish. Curtains isolated the tank from external disturbance. In addition to flourescent room light, a 150-watt flood light illuminated the test area to allow motion picture filming of fish activity. Water velocities were generated by a 1200 l/min pump and test velocities were determined by timing the travel of a float over a known distance. Differences in water velocity between the inner and outer channel walls at 15 cm/sec was negligible (<0.1 cm/sec at the surface) when tested with a float. Velocity measurements made at various depths with an electromagnetic current meter equiped with a microprobe indicated an increase in velocity variations as the probe was moved downstream within the test chamber.

Fish of 10 ($\pm$ 3), 25 ($\pm$ 5), and 50 ($\pm$ 3) mm total length were tested at velocities of 0, 3, 15, and 27 cm/sec with and without food present. Artemia nauplii were homogeneously distributed in the test chamber when experimental groups were tested for ability to forage at the various water velocities.

Groups of 20 juvenile striped bass were placed in the test chamber at 20 (± 1) C and allowed to acclimate for 30-min at 0 cm/sec. Any fish showing symptoms of stress or shock due to handling were replaced. In all cases shock and mortality due to handling were observed in less than 10% of the test group. The decision to use 20 individuals per test was based on preliminary observations. One 25-mm juvenile bass was placed in the test chamber and the activity recorded. Other striped bass were added one at a time and the activity of the first fish recorded after each addition. Visual contact is important in schooling fish and optimal density without crowding was determined.

Following acclimation, a series of several three-minute observations of the movements of individual fish were recorded and the entire test group was filmed for several minutes. The water velocity was increased, a 30-min acclimation period allowed, and observations again recorded. Voice recordings of numbers were taken from the background grid pattern as the observed fish moved within the test area. Activity was transposed to a paper replica of the grid pattern and the area covered during an activity period was calculated. For example, a 25-mm fish ranged 425 cm^2 per minute in a circular swimming pattern (Figure 3).

Individual frames from movies taken during observation periods for various combinations of fish size, velocity, and feeding were projected onto a piece of paper to determine

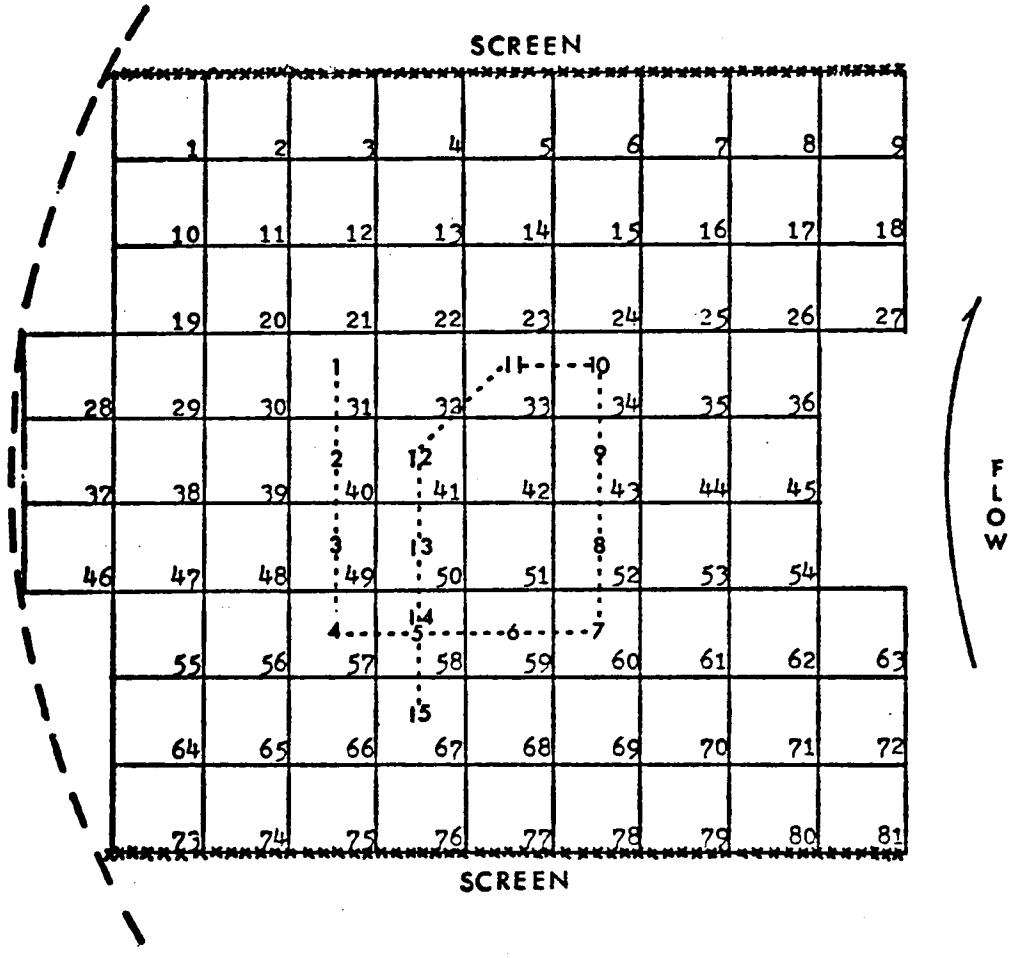

Figure 3. The 1-min activity pattern of a 25 mm juvenile striped bass at a water velocity of 15 cm/sec is superimposed on a replicate of the grid pattern used to monitor activity of juvenile bass 10 to 50 mm long.

distance between fish. A transect was drawn at a random distance from the projected image of the outer wall of the test chamber. At random points along the transect the distance between the premaxillaries of two fish on opposite sides of the line was measured. Three measurements were made for each of five frames taken from movies of the three sizes of fish under the four water velocities in the presence and absence of food, a total of 360 data points. Distance in centimeters was convereted to body lengths and regressed on velocity.

Movies were also used to analyze the orientation of the fish with respect to water current. Positive rheotaxis (P) described a fish actively swimming against the current, while negative rheotaxis (N) described downstream orientation. Lateral orientation (L) occurred when a fish positioned the long axis of its body perpendicular to stream flow. The orientation of 72 fish during three minute activity periods tested at combinations of velocity, fish size and the presence or absence of food was converted to percentage and the means calculated.

Data obtained from the test groups were subjected to three treatments. Analysis of variance was used to assess the signifance of fish size, water velocity, and presence/absence of food on the total area occupied by individual fish. The effect of water velocity and feeding activity on the distance between fish was analyzed. The mean percentage of time spent in positive, lateral, and negative

rheotaxis describing the relationship of a swimming fish orienting with respect to three water velocities was compared.

Juvenile II Striped Bass Observations

The experimental procedure for this set of experiments was similar to that used in observations of entrainable juvenile I striped bass. The modified 180 cm-diameter tank, 1200 l/min pump, fluorescent lighting and curtain isolating the test tank all remained the same. Twelve millimeter heavy-duty mesh screens similar to those currently used in intake structure were placed at the upstream and downstream ends of the test chamber. Background grid pattern changes were also necessary to accomodate impingeable striped bass of 80 (± 7) mm total length. Individual squares were enlarged to 10 x 10 cm and the test area now measured 5,300 cm^2 (Figure 4).

Effects of interactions between velocities of 0, 5, 15, and 30 cm/sec and temperatures of 5, 10, 15, 20, 25 and 30 C on the area ranged and distance traveled by juvenile striped bass were investigated. Fish were acclimated from holding temperatures at the rate of 1 C per day until final test temperature was obtained. All juveniles were acclimated at test temperatures for at least seven days prior to velocity testing.

Groups of 10 striped bass were placed in the test chamber. In each case experiments were conducted at the

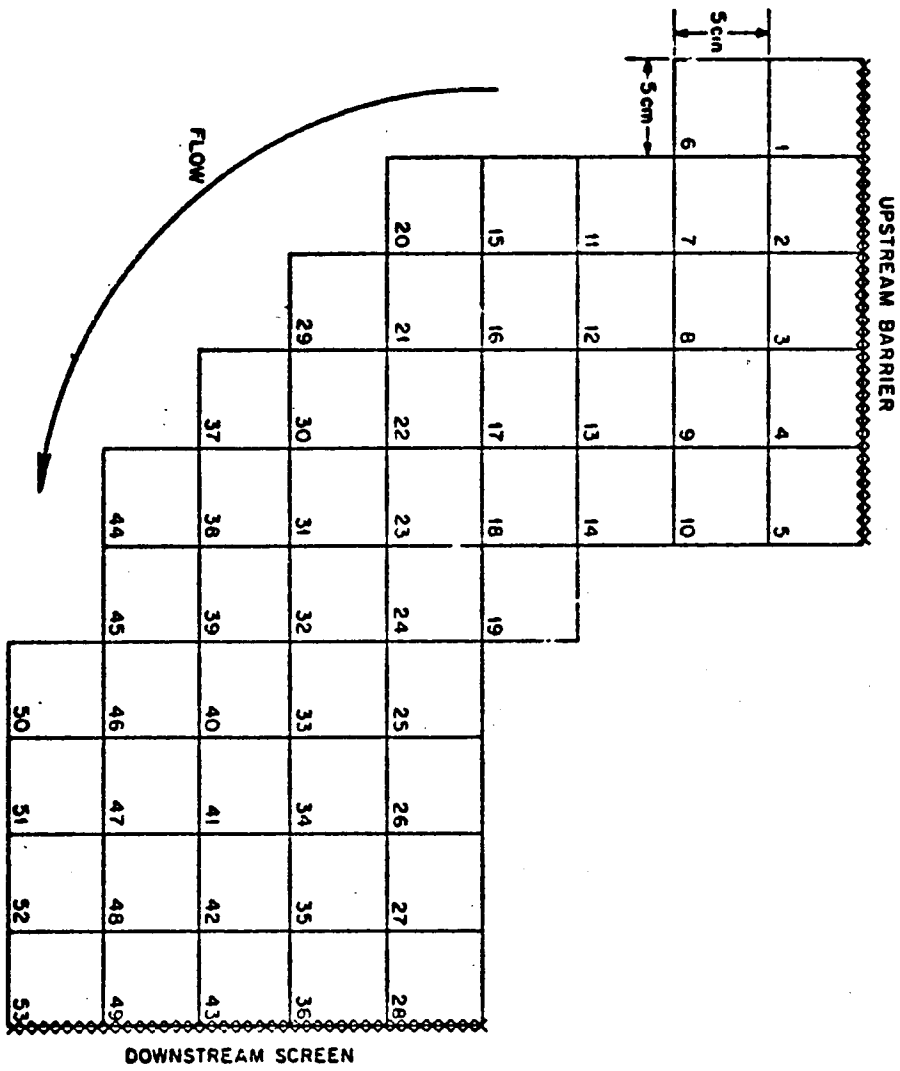

Figure 4. The background grid pattern for monitoring activity of 80 mm juvenile striped bass.

acclimation temperature ± 1 C. A 30-min waiting period at 0 cm/sec allowed the juveniles to recover from handling stress induced by netting and transfering from holding tanks to the test chamber. The pump was started, the desired velocity obtained, and observations begun. Observation periods lasted five hours for each temperature and velocity combination. Observations again consisted of voice recordings of grid numbers for fish which moved across a background grid pattern drawn on the floor of the tank. Three recordings of individual fish were made at each time interval: 15, 30, 45, 60, 90, 120, 150, 180, 210, 240, 270, and 300 min. As before, numbers were transferred to a paper replica of the background grid.

Data were analyzed using three-way analysis of variance to test the significance of temperature, velocity, and length of time swimming on the area covered and distance traveled by impingeable-size striped bass. Mean percentage of movements which were oriented positively, negatively, and laterally to flow were analyzed.

Some additional investigations were conducted. At 20 C and velocities of 15 and 30 cm/sec a large eddy current was generated in the test chamber to observe effects of turbulence on the swimming performance of fish. In another series of experiments at 15 C and flows of 15 and 30 cm/sec, a fish blinded by ocular puncture in both eyes was introduced with 9 normal conspecifics and behavioral observations made.

Data obtained from turbulence and blind fish experiments were compared to temperature/velocity data obtained from other juvenile striped bass.

CHAPTER V

RESULTS

Results of Larval Striped Bass Observations

Activity of striped bass less than 10 mm long was greatly influenced by a small change in velocity. Analysis of variance indicated an increase in velocity from 0 to 3 cm/sec caused a highly significant ($P<0.001$) decrease in both the area (Table 1) and distance (Table 2) traveled by larval fish. Great similarity in the magnitude of the F-values for the effects of water velocity on area and distance traveled were observed when the two tables were compared. The effect of presence or absence of natural food on the area and distance traveled by larval striped bass was less than the effect of velocity, but still highly significant ($P<0.001$). Again, a comparison of the F-values revealed the two values, distance and area, had similar magnitude. Interactions between water velocity and presence/absence food were not significant ($P>0.05$).

At both 0 and 3 cm/sec striped bass traveled greater distances with food available than without food (Figure 5A). Area ranged by 12 individuals during 1-min observations also increased when food was present (Figure 5B). Visual observations indicated larval striped bass fed continuously. Feeding activity accounted for most locomotion at 0 cm/sec.

Table 1. Analysis of variance showing the effect of water velocity and the presence of food on area traveled by larval striped bass during 1-min observation periods.

Source of Variation	df	MS	F
Water velocity	1	47,062.7	146.2[a]
Food present/absent	1	8,034.2	24.9[a]
Water velocity x food	1	15.2	0.1[b]
Error	44	322.0	--
Total	47	1,474.0	--

[a]Significant at P<0.001

[b]Not significant at P<0.05

Table 2. Analysis of variance showing the effect of water velocity and the presence/absence of food on distance traveled by larval striped bass during 1-min observation periods.

Source of Variation	df	MS	F
Water velocity	1	5,874.2	135.7[a]
Food present/absent	1	1,912.7	44.2[a]
Water velocity x food	1	1.7	0.1[b]
Error	44	43.3	--
Total	47	206.2	--

[a]Significant at P<0.001

[b]Not signficant at P<0.05

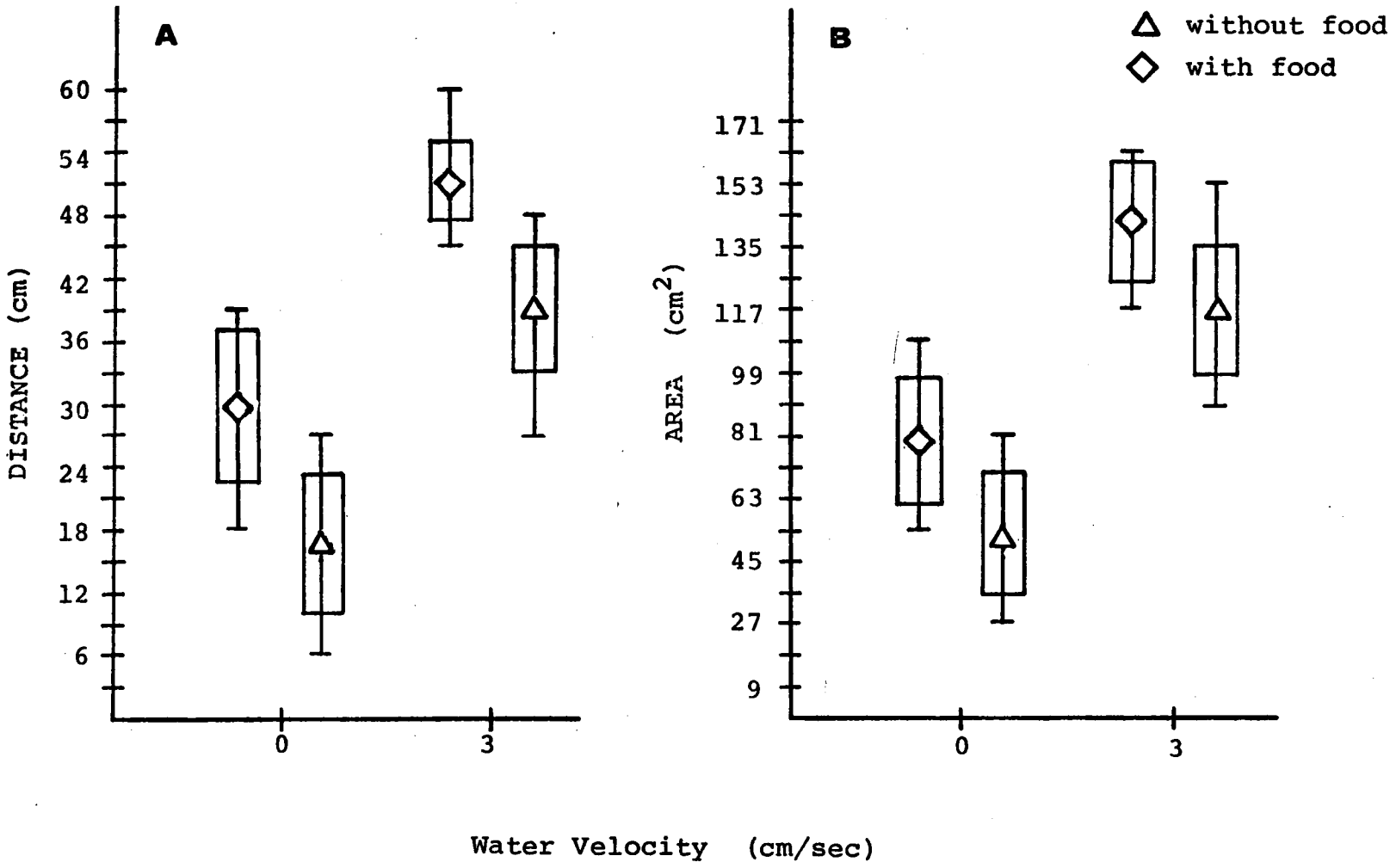

Figure 5. Distance traveled (A) and area ranged (B) by larval striped bass at two velocities during 1-min activity periods. Bars indicate one standard deviation and symbols show the mean. Brackets represent the range of twelve samples.

Larval fish tested at 0 cm/sec without food present generally sank slowly. One individual came to rest on the plastic observation grid and remained in stationary contact for several minutes. Food organisms were generally positively phototactic and remained near the surface of the tank. Large numbers of young striped bass cluster at the water surface near aggregations of Daphnia.

Larval bass covered more distance and area in the higher velocity flow. When the water velocity increased to 3 cm/sec most food organisms drifted with the water flow. Striped bass fry repeatedly oriented upstream, swam a short distance while feeding, and then drifted downstream. When no food was present at 3 cm/sec, larval bass alternately swam and drifted for short distances.

Area and distance covered increased proportionately (Figure 6). Area and distance were plotted simultaneously and a line indicating those points where distance and area had a one to one relationship was drawn. Points above the line indicated a circular swimming pattern. Points falling on the line indicated unidirectional movement. Points below the line represented individuals displaying the swim/drift activity pattern. Few circular swimming patterns were exhibited by larval bass. The swim drift activity pattern occurred most frequently.

No fright response was observed in larval striped bass less than 10 mm long. There was no indication the young bass were aware of motion or presence of the investigator. A hand

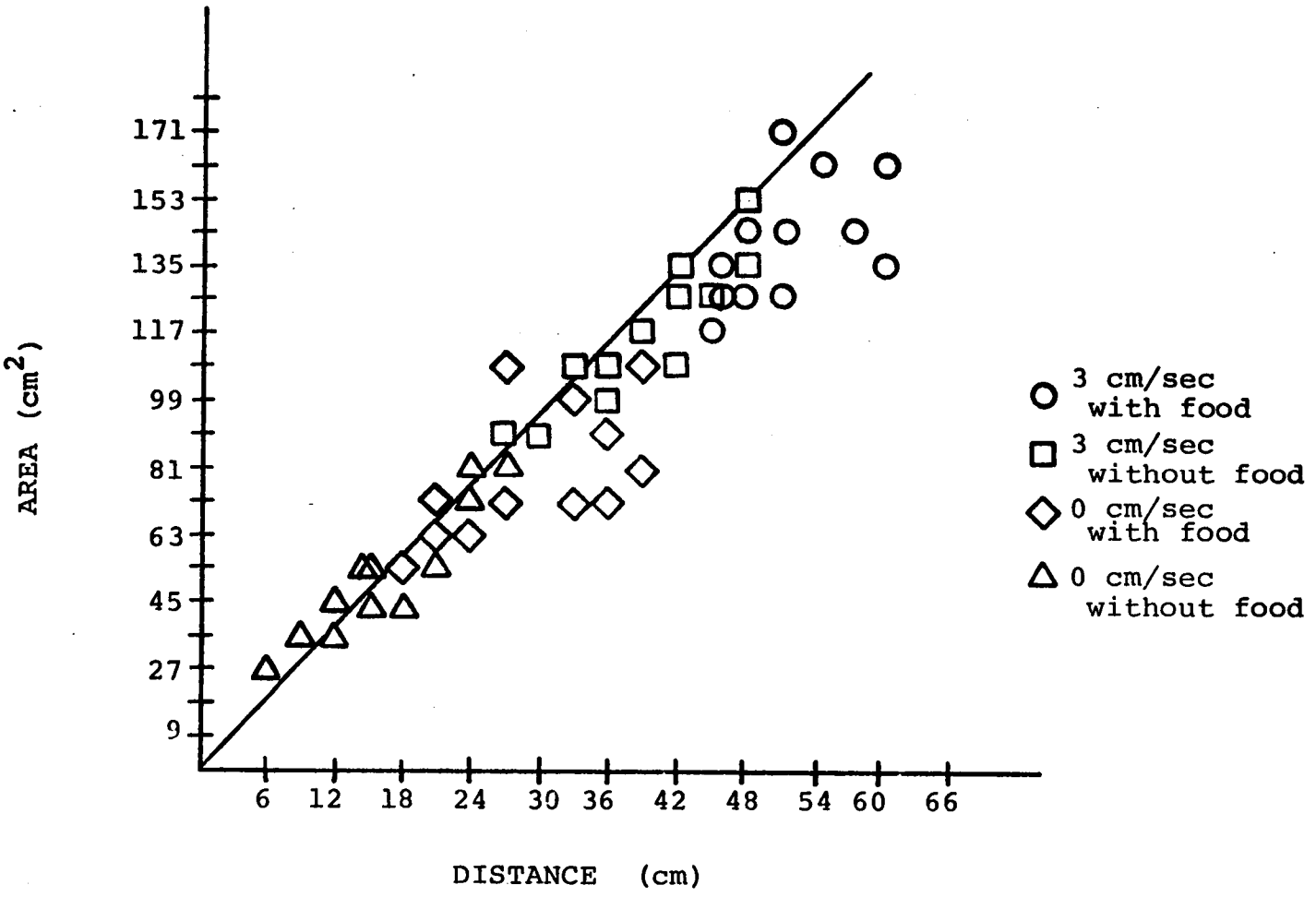

Figure 6. . Area and distance traveled by larval striped bass at 0 cm/sec and 3 cm/sec with and without food present. The line indicates a 1:1 relationship of distance: area traveled.

passed quickly a few centimeters above the water surface caused no response, yet even the gentlest handling caused high mortality.

No schooling activity was observed; each individual moved independently of other bass. Some visual cueing was observed in the feeding response. Although larval fish occupied the entire 90 cm vertical water column, the greatest number were within 30 cm of the surface whether food was present or not.

Results of Juvenile I Striped Bass Observations

Area occupied by a single 25-mm striped bass was monitored as 19 additional bass were placed in the test chamber one at a time (Figure 7). The original striped bass occupied less and less area until a total of 12 juveniles were present. A total of 20 fish were placed in the tank, but after the first 12 individuals were added little change in area occupied was observed. No apparent crowding stress was observed when experimental groups of 20 were used.

Of the variables tested, water velocity had greatest significnat impact on area traveled during 3-min activity observations (Table 3). Area decreased as velocity increased. Fish size and presence or absence of food had lesser, yet highly significant effects on range. Interaction between water velocity and fish size was more significant than other interactions affecting area juvenile striped bass were able to cover.

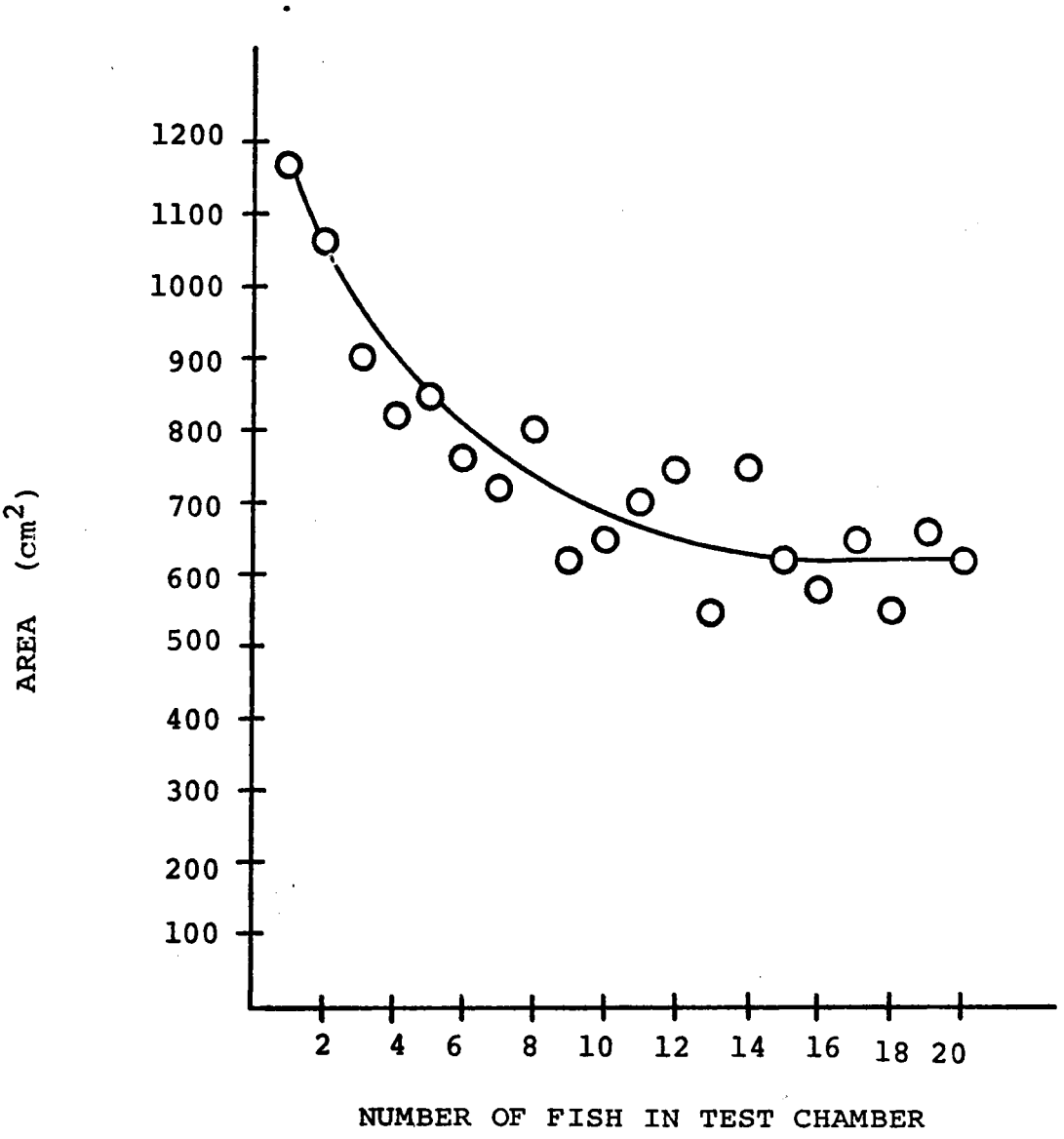

Figure 7. Area traveled during a 3-min observation period as a function of the number of 25 mm juvenile striped bass present in the test chamber. The curve was fitted by eye.

Table 3. Analysis of variance showing the effect of fish size, water velocity, and presence/absence of food on the area traveled by juvenile striped bass 10 to 50 mm long during 3-min observation periods

Source of Variation	df	SS	MS	F
Water Velocity	3	112,563.9	37,521.3	8,128.2[a]
Fish Size	2	35,902.6	17,951.3	3,888.8[a]
Food Present/Absent	1	956.0	956.0	207.1[a]
Water Velocity X Fish Size	6	4,580.5	763.4	165.4[a]
Water Velocity X Food	3	249.2	83.1	17.9[a]
Fish Size X Food	2	384.2	192.1	41.6[a]
Velocity X Size X Food	6	70.2	11.7	2.5[b]
Error	216	997.1	4.6	--

[a]Significant at $P<0.001$.

[b]Not Significant at $P<0.05$.

Increased water velocity significantly decreased the area ranged by 10, 25, and 50-mm juvenile striped bass in the absence of food ($P<0.05$)(Figure 8A). No significant difference was found among the slopes of the regression lines for the three fish sizes, indicating that the magnitude of the area covered was proportional to the size of the fish. Area covered by 10-mm juveniles during 3-min activity periods at 27 cm/sec was nearly an order of magnitude less than area covered under static conditions.

Presence of brine shrimp (Figure 8B) significantly reduced the area ranged by all juvenile fish tested ($P<0.01$). The small size of the food organisms may have biased the data. Fish 10 and 25-mm in length reacted quickly and visibly to the presence of food while the reaction of 50-mm fish was subdued and nearly imperceptible. Area foraged by juvenile fish was porportional to fish size. For all juveniles tested the effects of increased water velocity were more marked in the absence of food.

Distance between fish decreased as water velocity increased (Figure 9). The presence of food significantly ($P<0.05$) reduced distance between 10 and 25-mm striped bass. Spacing between 50-mm juveniles was not significantly reduced by the presence of food. The 10-mm fish under static conditions maintained the greatest inter-fish distance in body lengths between fish. Actual body contact was observed infrequently among 10-mm bass at 27-cm/sec and no contact

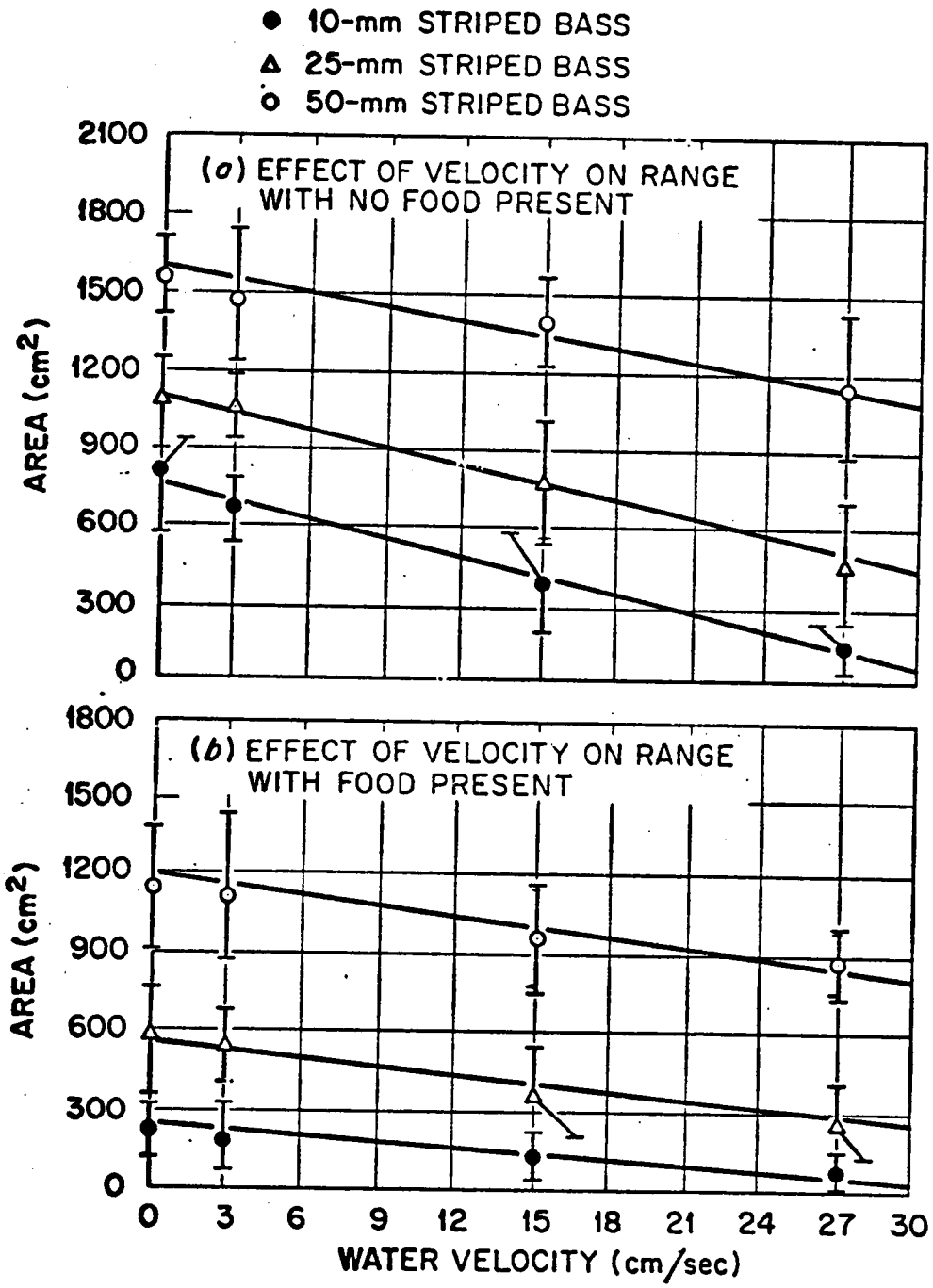

Figure 8. The effect of increasing velocity on juvenile striped bass mobility in the presence and absence of food. Each data point represents mean area occupied by 20 each of fish during a 3-min observation period. Brackets show one standard deviation.

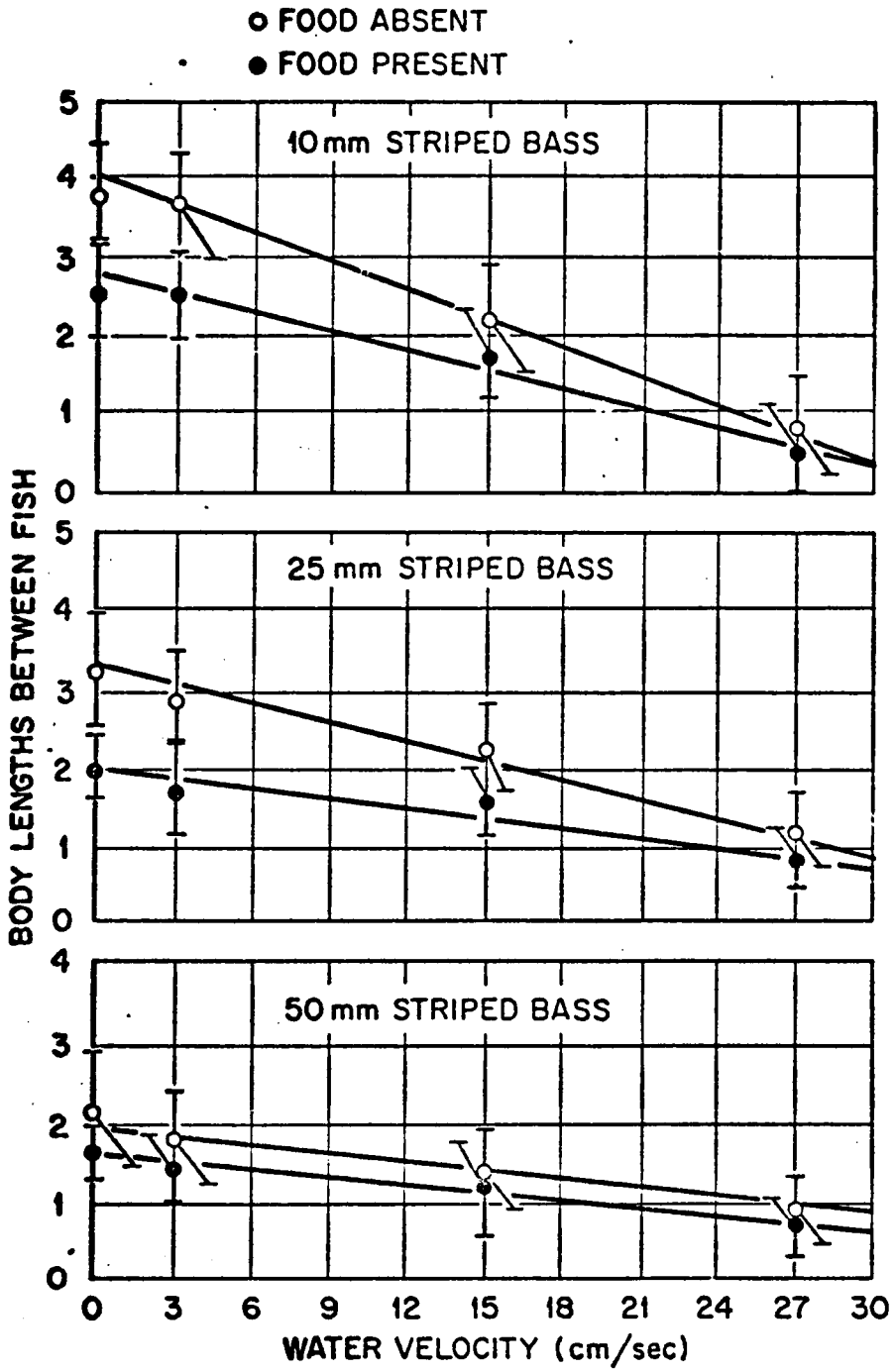

Figure 9. The relationship of water velocity and distance between fish for 3 sizes of juvenile striped bass. Each point represents the mean from 15 samples. Brackets show one standard deviation.

was observed for larger fish. A minimum spacing equal to at least 0.5 body length was maintained by the majority of test fish.

Positive rheotaxis was generally the dominant orientation and was exhibited 25 to 81% of the duration of each observation (Figure 10). At a water velocity of 3 cm/sec young striped bass spent nearly equal amounts of time in positive, lateral and negative rheotaxis. Lateral rheotaxis decreased as velocity increased ranging from 40% at 3 cm/sec to 3% at 27 cm/sec. Negative rheotaxis was variable, but generally decreased as velocity increased ranging from 39% to 8% of a 3-min activity period. Presence of food had little impact on rheotactic response.

When no food was present young striped bass often remained in the lower third of the 30-cm deep water column. Occasionally 25 and 50-mm fish rose to the upper third of the water column under low flow conditions. At 27 cm/sec all fish observed remained very close to the bottom of the test chamber. Little attraction to the sides of the test chamber was observed.

When food was present vertical movement occurred throughout the water column at all water velocities tested except 27 cm/sec. A weakly sterotyped feeding sequence was observed. Once visual contact with prey was made, young bass darted upstream quickly, engulfed the organism, and sank down within the water column about two body depths.

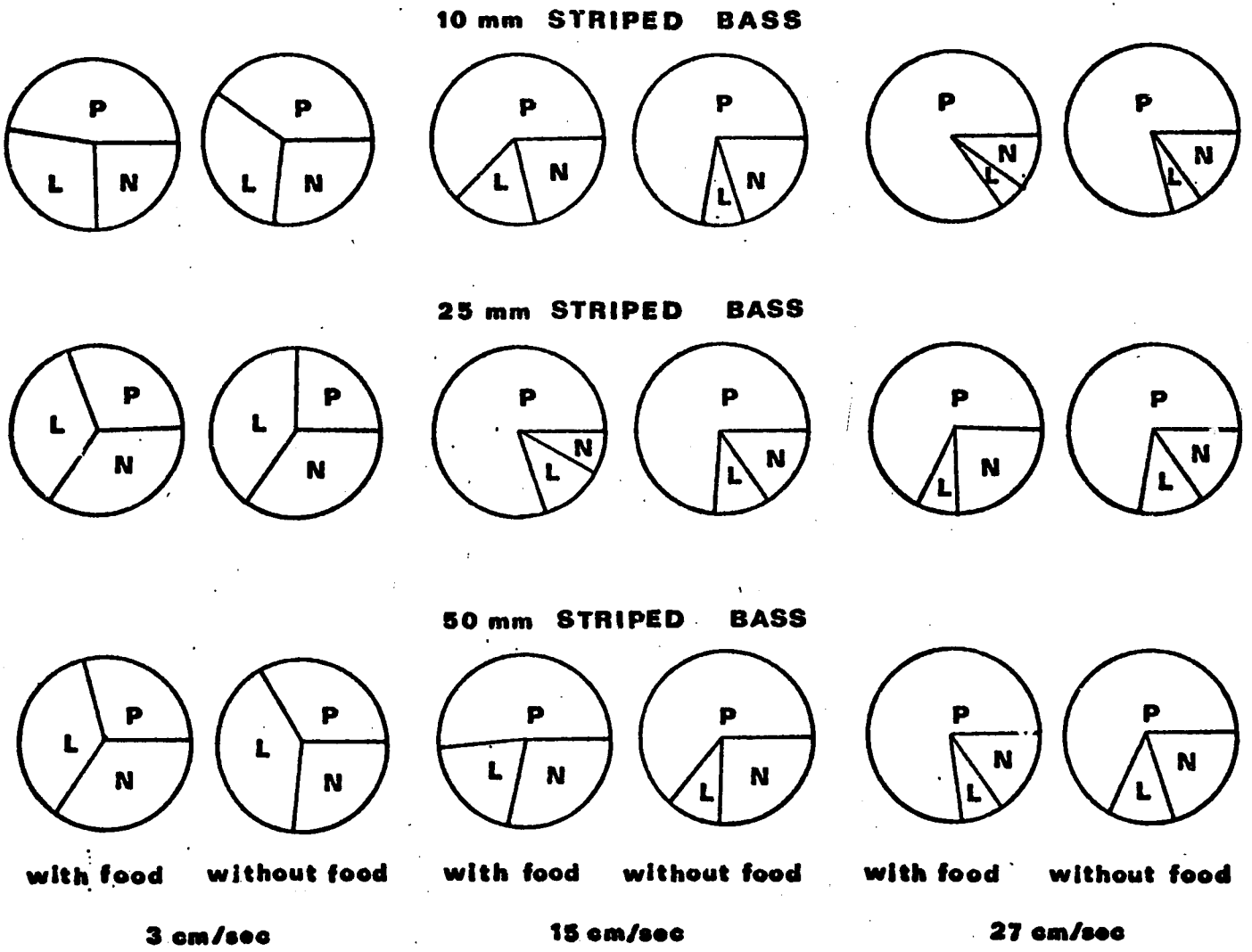

Figure 10. Mean percentage of the 3-min observation spent in positive (P), negative (N), or lateral (L) rheotaxis at the various test velocities. Each section represents the mean of 3 observation periods.

Fish then returned to approximately the area where prey had first been sighted. Several feeding sequences were rapidly repeated in the same location. Awareness of the downstream screen apparently decreased during feeding; several apparently unstressed fish made caudal fin contact with the screen at velocities of 15 and 27 cm/sec.

All 25-mm juvenile striped bass displayed a swimming posture different from other size fish. While 10 and 50-mm bass swam with the long axis of the body parrallel to the bottom of the tank during all activity except vertical movement, over 100 measurements made on isolated frames of movie film showed 25-mm fish swam constantly at a heads-up angle of 20° ($\pm$ 3° s.d.) with respect to the bottom of the tank.

Results of Juvenile II Striped Bass Observations

Analysis of variance demonstrated water temperature had the most significant ($P<0.001$) effect on area ranged (Table 4) and distance traveled (Table 5). Water velocity and length of time swimming had a lesser, yet still significant ($P<0.001$) influence on the area and distance covered by 80 mm juvenile striped bass during one minute observations. When the two F-values were compared area values were consistently greater than distance values in all highly significant interactions.

Area and distance traveled decreased as water velocity increased (Figure 11). Mean values of 72 samples tested at each speed went from 187 cm traveled while ranging a mean area

Table 4. Analysis of variance showing the effect of temperature, water velocity, and duration of the experiment on area ranged by juvenile striped bass 80 mm long.

Source of Variation	df	MS	F
Water Temperature	5	163,000.5	1303.8[a]
Water Velocity	3	82,274.5	658.1[a]
Time Swimming	11	11,561.9	92.5[a]
Velocity X Temperature	15	2,544.8	20.4[a]
Velocity X Time	33	179.5	1.4[b]
Time X Temperature	55	115.7	0.9[c]
Error	165	125.0	--

[a]Significant at P<0.001

[b]Significant at P<0.05

[c]Not Significant at P<0.05

Table 5. Analysis of variance showing the effect of temperature, water velocity, and duration of the experiment on distance traveled by juvenile striped bass 80 mm long.

Source of Variation	df	MS	F
Water Temperature	5	158,121.4	589.5[a]
Water Velocity	3	60,255.6	224.6[a]
Time Swimming	11	6,921.2	23.4[a]
Velocity X Temperature	15	2,320.8	8.7[a]
Velcoity X Time	33	326.1	1.2[b]
Time X Temperature	55	250.9	0.9[c]
Error	165	268.1	--

[a]Significant at P<0.001

[b]Significant at P<0.05

[c]Not significant at P<0.05

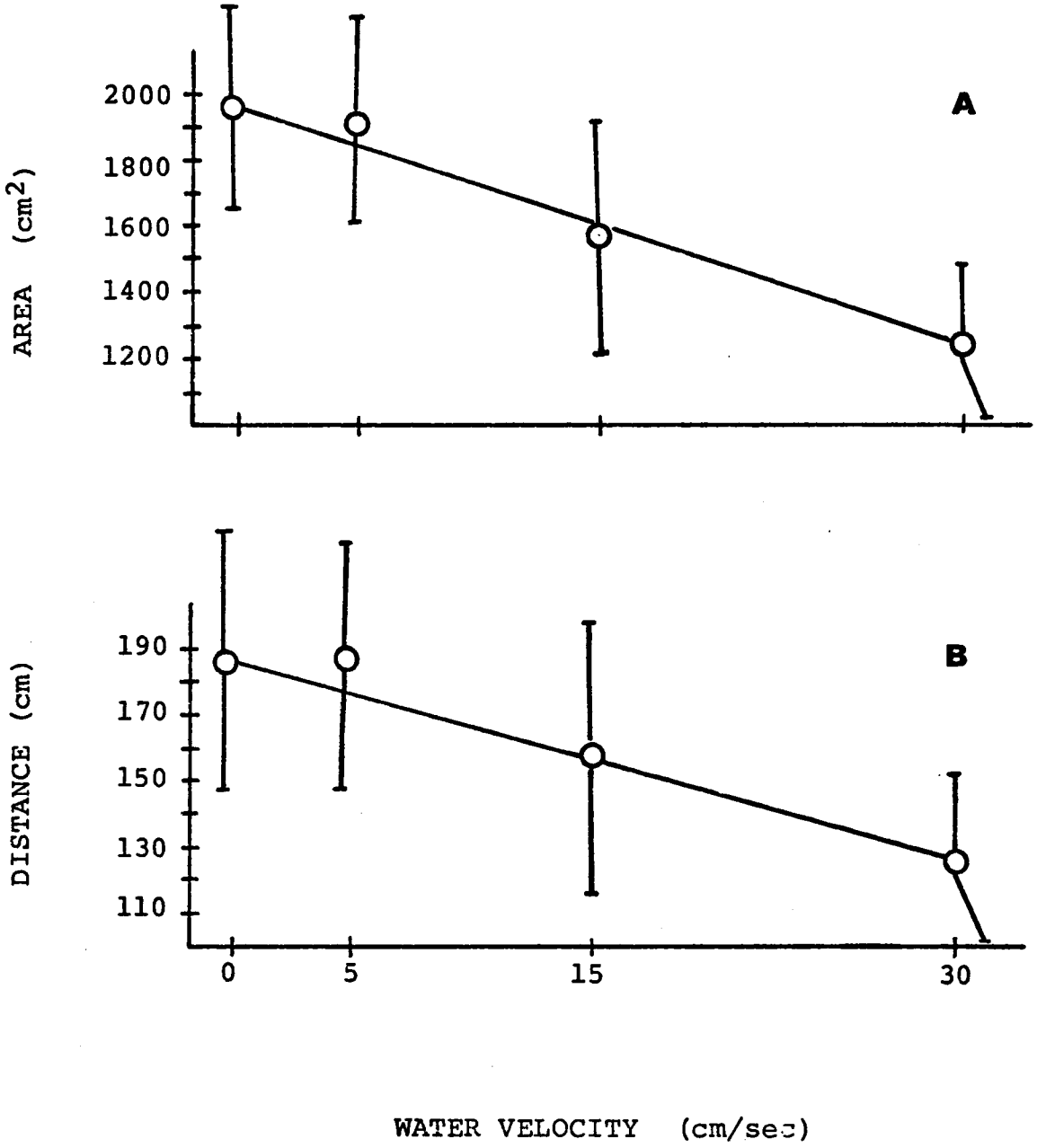

Figure 11. Area ranged (A) and distance traveled (B) by 80 mm striped bass at four water velocities. Points represent the mean of 72 samples and brackets show one standard deviation.

of 1968 cm^2 at a velocity of 0 cm/sec to 127 cm traveled while ranging a mean area of 1236 cm^2 at a velocity of 30 cm/sec.

Area and distance traveled increased with increasing temperature up to 20 C, then declined at higher temperatures (Figure 12 and 13). Both results had a maximal value near 20°C. Distance traveled and area occupied reached maximal mean values of 231 cm and 2350 cm^2 respectively.

Both area and distance traveled decreased as the length of time the striped bass had been swimming increased (Figure 14). Again the relationship for both measures of activity was similar. During the first 60 min of an observation juvenile striped bass displayed an exploratory action pattern. Large areas of the test chamber were quickly examined by the test group. Rapid darting motions characterized by abrupt directional change were typical. After 90 min the activity decreased slowly as length of time the fish remained swimming increased. At the end of five hours under all velocities observed, actitivy was noticably reduced. The distances at the 300-min observations ranged from 10 cm traveled at 5C to 230 cm traveled at 25 C.

Polarized schooling, all individuals having similar orientation and moving synchronously, was fully developed in all 80 mm striped bass observed. The 10 individuals in each test group generally maintained the same orientation and moved about the test chamber as a unit. At velocities of 15 and 30 cm/sec striped bass tended to "line up" in

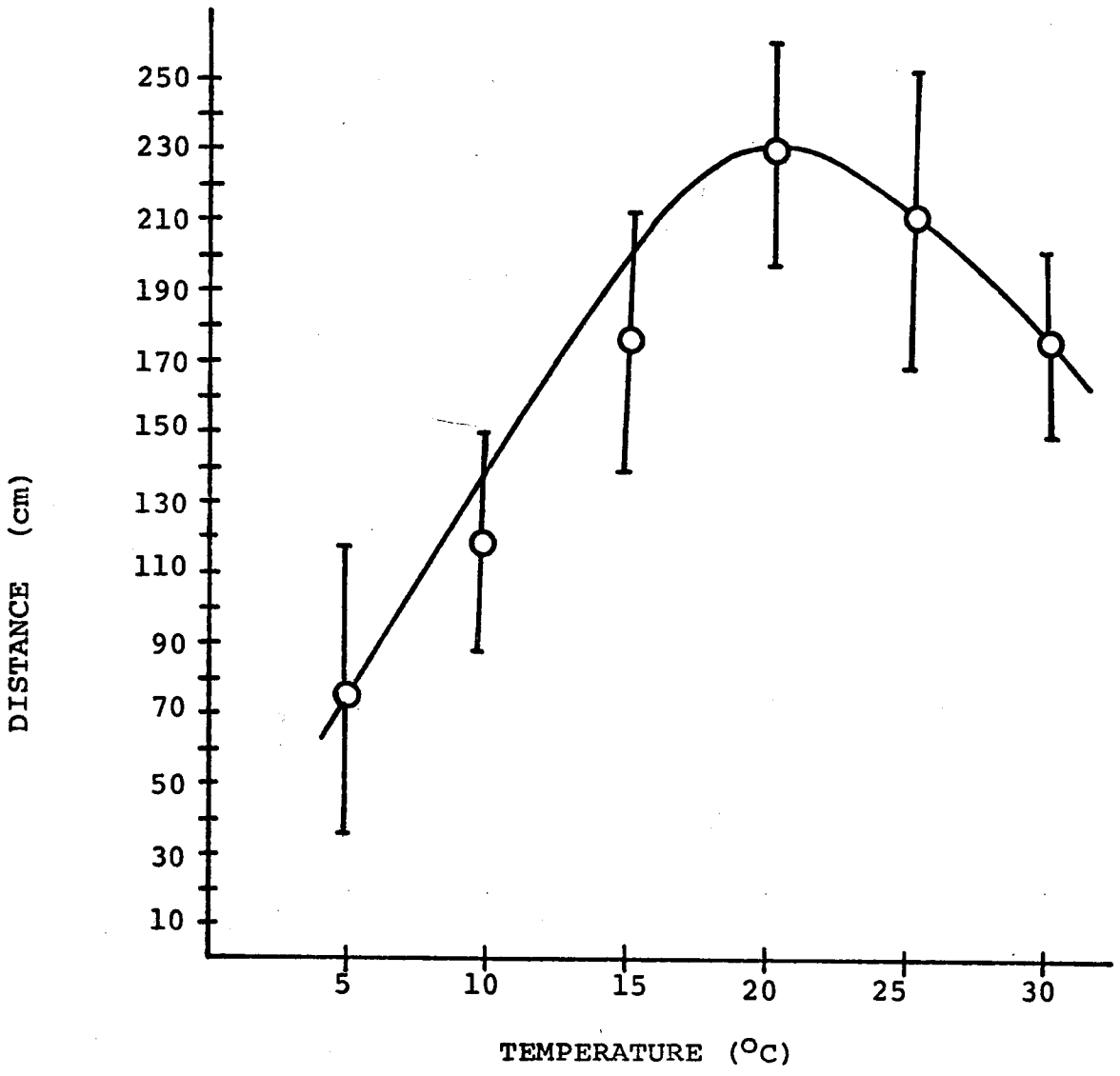

Figure 12. Thermal effects on distance traveled by 80 mm juvenile striped bass. Curve was fitted by eye. Points represent means of 48 samples and brackets show one standard deviation.

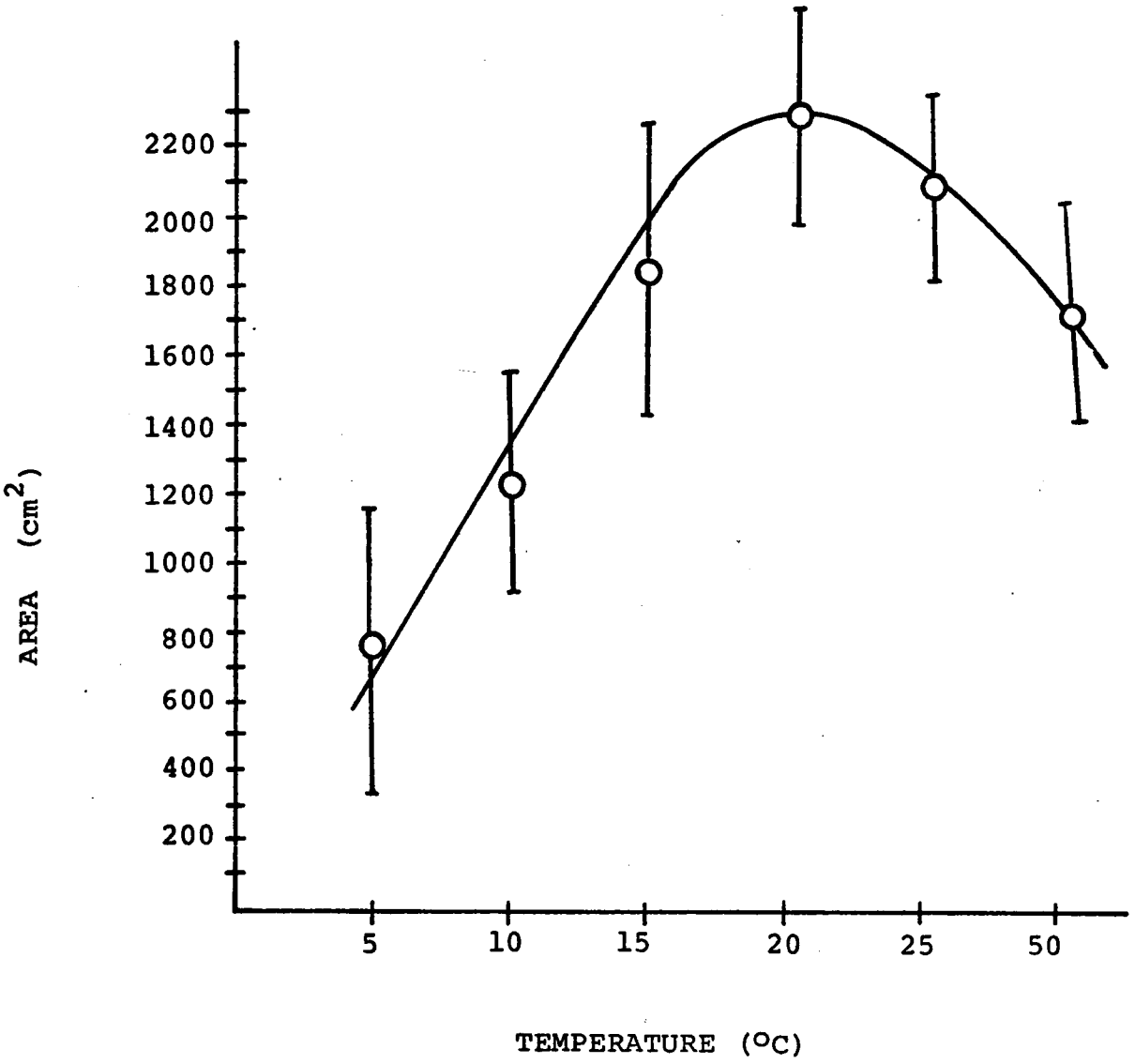

Figure 13. Thermal effects on area ranged by 80 mm striped bass. Curve was fitted by eye. Points represent means of 48 samples and brackets show one standard deviation.

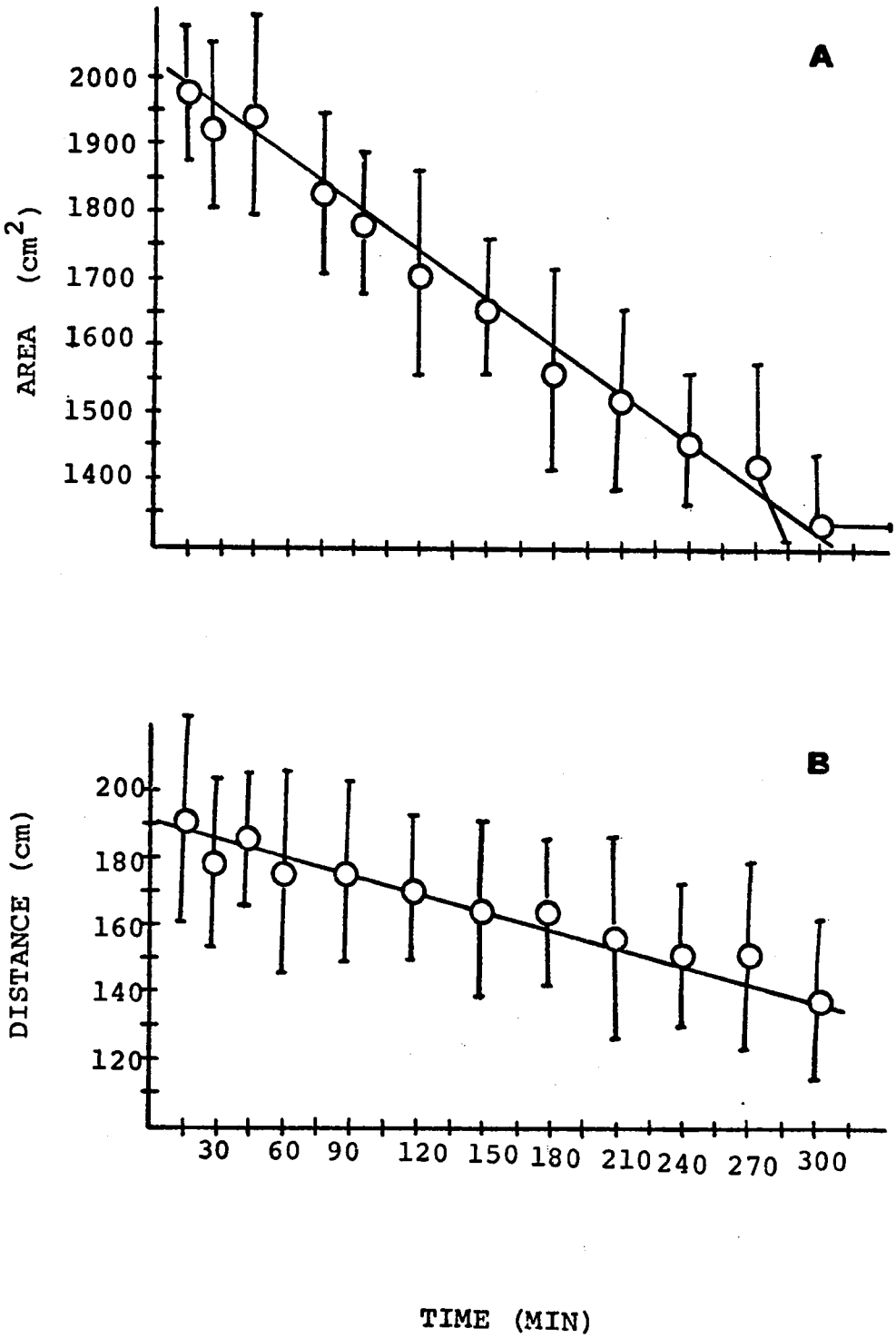

Figure 14. Effects of length of time fish had been swimming on area ranged (A) and distance traveled (B) by 80 mm juvenile striped bass. Each point represents the mean of 24 samples and brackets show one standard deviation.

two horizontal rows of five near the upstream screen. Side-to-side spacing in the two rows was very uniform, approximately 3 to 5 cm between individuals depending on the water velocity. Generally, the two rows were staggered so that juveniles in the back row occupied the space to the rear of and between two juveniles in the front row. Positions in the rows were alternated so no individual occupied the upstream position continuously. Distance between the upstream screen and the fish increased as velocity increased.

Area ranged by blind and sighted fish (Figure 15) at 20 C during 1-min observations differed significantly ($P<0.001$). At both 15 and 30 cm/sec blind fish frequently struck the upstream and downstream screens isolating the test chamber from the remainder of the tank. Generally, the blind fish would locate an area of reduced velocity near the outer wall and remain in that area. Blind striped bass occupied all depths of the water column and most frequently occupied the upper third of the vertical cross-section. Initially, blind juveniles would break the surface of the water. Rapid, uneven swimming with frequent changes in depth and direction characterized activity during the first 30-min. Other sighted juvenile striped bass present in the same test chamber occasionally attempted to school with the blind fish, but these attempts were of short duration. The blind fish never reacted to the presence of conspecifics in the test chamber. At a water velocity of 30 cm/sec the blind bass was repeat-

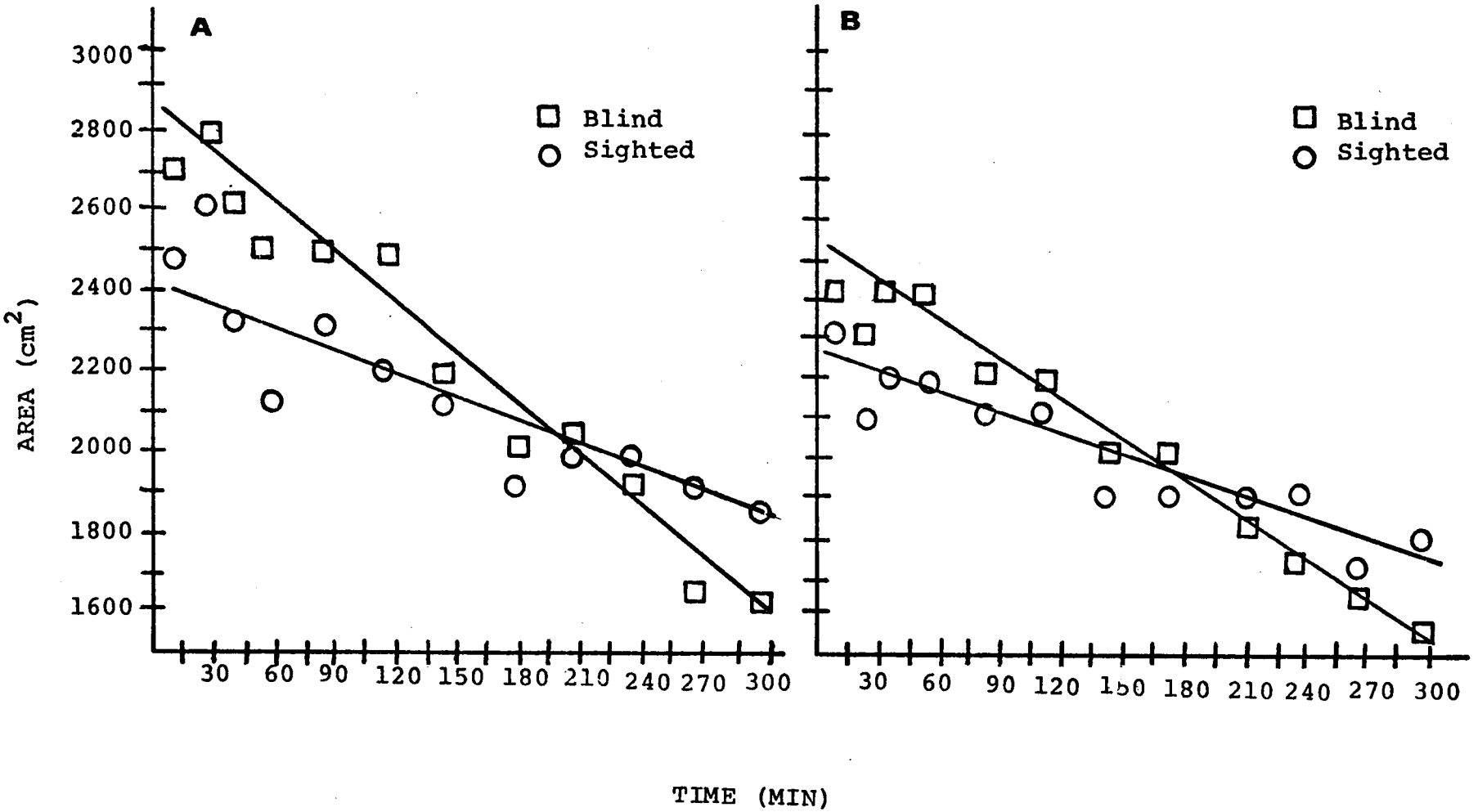

Figure 15. Area ranged by blind and sighted juvenile striped bass during activity periods at 20 C at water velocities of 15 cm/sec (A) and 30 CM/sec (B).

edly impinged for a few seconds, but managed to free itself from the screen.

A single large eddy purposely generated in the test chamber increased the area juvenile striped bass ranged at 15 C during one-minute observation periods (Figure 16). The increase in area ranged was greater at a water velocity of 30 cm/sec than at a water velocity of 15 cm/sec. Behavioral observations indicated 80 mm juvenile striped bass first display an exploratory action pattern when encountering the eddy. Several hours later young bass attempted to swim in the swiftest and least turbulent area of the eddy. At first juveniles traveled with the circular flow of the eddy in an exploratory manner. For several hours, juvenile bass maintained a position in the swiftest portion of the eddy always orienting upstream. Much later, as fatigue increased, the bass again traveled with the circular current. To maintain positive rheotaxis the body of the fish rotated around the central node of the eddy.

Rheotaxis was sensative to changes in water velocity, but not to changes in water temperature. As velocity increased positive rheotaxis increased and lateral rheotaxis decreased. The relationship between negative rheotaxis and velocity was variable. Temperature had no effect on rheotaxis of juvenile striped bass (Figure 17).

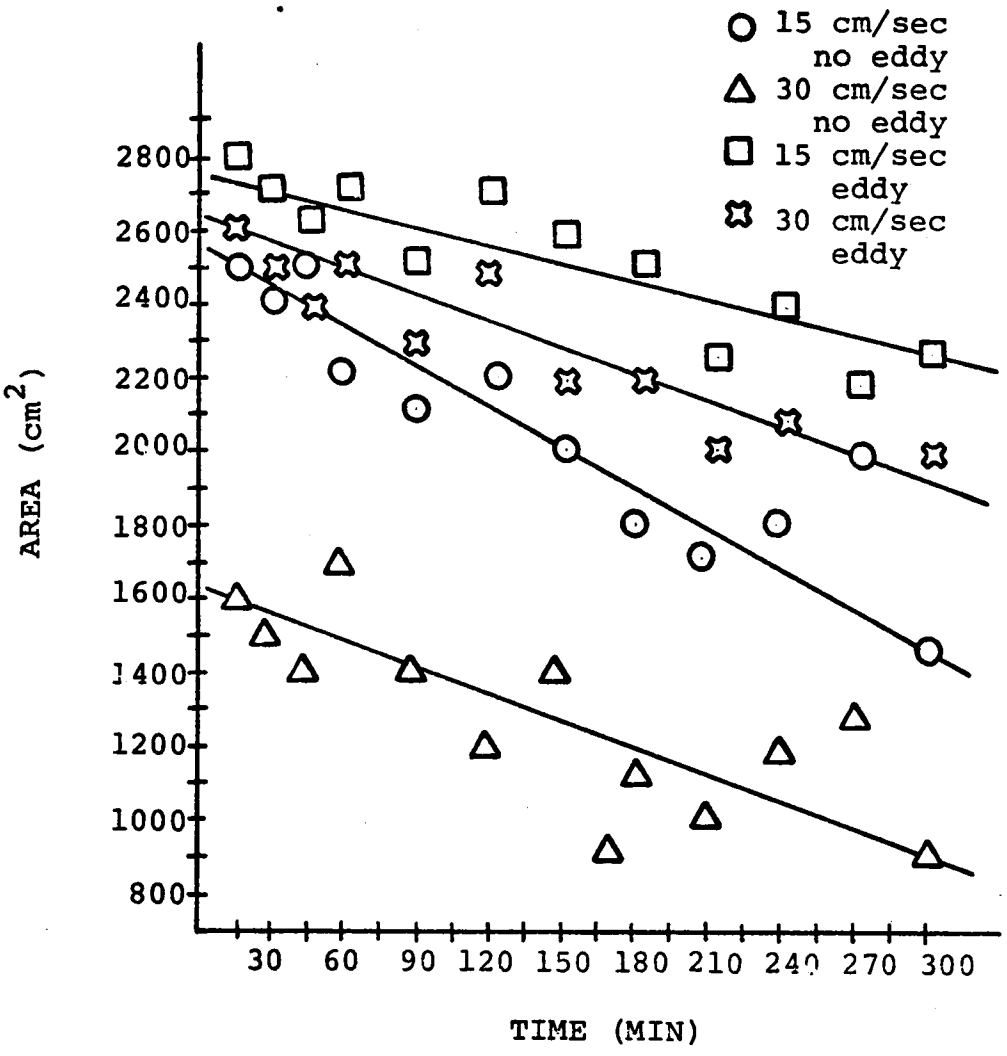

Figure 16.. Area ranged by 80 mm juvenile striped bass with or without an eddy current at 15 C during 1-min activity periods.

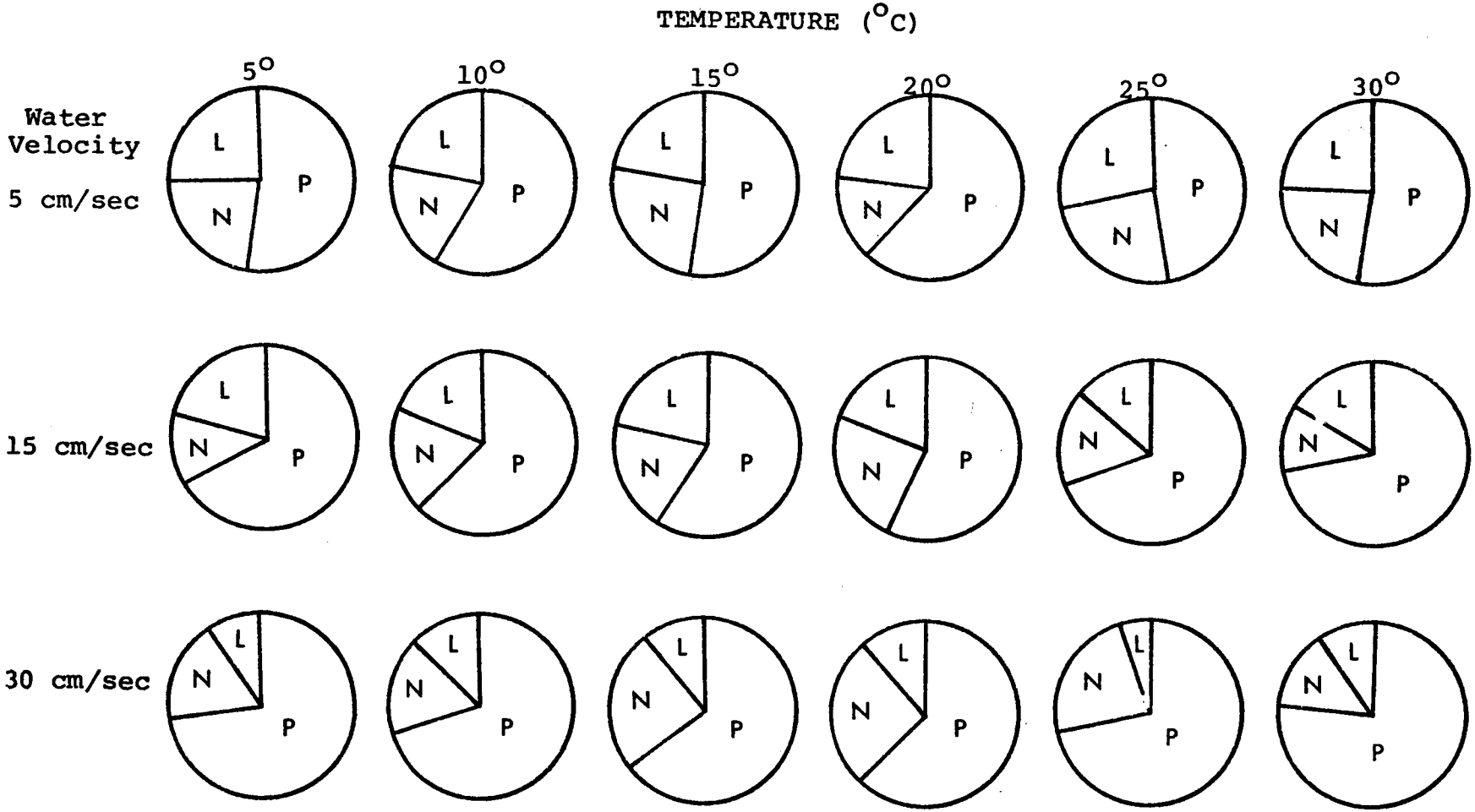

Figure 17. Relationship of rheotaxis at water velocities and temperatures tested. Each circle represents the mean percentage of time fro 36 samples spent in positive (P), negative (N), and lateral (L) rheotaxis during 1-min observation periods.

CHAPTER VI

DISCUSSION

Water velocity had a highly significant impact on the area and distance traveled by striped bass 8 to 80 mm long. As water velocity increased the activity of juvenile I and II bass decreased. In contrast, as the water velocity increased from 0 to 3 cm/sec the activity of larval bass increased. Entrainable larval bass demonstrated poor swimming ability, exhibited frequent drift behavior, and remained stationary for minutes occasionally. Juvenile I bass were more active swimmers than larval bass and little time was spent drifting or stationary. All juvenile I striped bass tested at the 27 cm/sec water velocity would be susceptible to entrainment because they lack the substantial ability to make forward progress that is necessary to escape a water intake structure. Juvenile II striped bass exhibited a marked increase in swimming ability over younger bass.

The swimming ability and survival of juvenile striped bass observed in these experiments was slightly greater than values perviously reported. Kerr found 100% survival by striped bass 25 to 75 mm long tested at 30 cm/sec for 10 minutes. Juvenile striped bass 18 to 37 mm long experienced 80% endurance under the same experimental conditions. Skinner (1974) found 90% of striped bass 40 to 50 mm long

were able to swim at velocities of 24 cm/sec for a 6 minute test period. The results, Skinner explained, were lower than values commonly found in the literature due to differences in experimental procedure and pretest handling (juveniles were held in static water). Bibko et al. (1974) found larger striped bass 89 to 138 mm long maintained a sustained swim speed of 27 to 60 cm/sec. Bainbridge (1958) demonstrated exercise did improve swimming performance and juveniles tested in this research were held in acclimation tanks at a maximum water velocity of 3 cm/sec for at least a week prior to testing. The length of test chamber acclimation may have also increased the swimming activity of bass reported here. Very little time was allowed by most investigators for recovery from handling and initial exploration. Laurence (1972) allowed 15 min. For the investigations reported in this work a 30 min acclimation period without current was allowed for each test and such a long acclimation period may have increased swimming activity.

When food was present area and distance traveled by larval striped bass increased. Drift behavior was exhibited as frequently as active swimming in the presence of food, but without food present active swimming occurred even less frequently. When no water flow was present, a condition larval bass rarely face in nature, feeding patterns were the primary source of motion. The reduction in activity when no food was present was dramatic. Several individuals made contact with the observation grid and remained stationary

in the still water for periods ranging from several seconds to several minutes. In similar feeding studies, Lawrence (1972) observed plankters stimulated larval activity and larvae tested without food remained on the bottom of the test tank. Juvenile striped bass observed in this study covered less area when food was present. Distance between juvenile I bass was reduced during feeding and visual cueing seemed to play an important part in triggering feeding sequences. Perception of the downstream screen decreased to the point of repeated tail contact in several groups tested with food present in this investigation.

Low water temperature has frequently been considered a major cause of increased winter impingement mortaility (Sonnichsen, et al., 1973; e.g. Bibko, et al., 1974). Griffith and Tomljanovich (1975) found a correlation between seasonal low temperature and increased threadfin shad (Dorosoma petenense) impingement at five of twelve power plants surveyed in the southeast. Larval and juvenile I bass in this study were tested at only 20 C, a temperature reflecting encironmental conditions faced in the field during late spring and early summer. Juvenile II bass were tested at temperatures ranging from 5 to 30 C, since young bass could encounter these temperatures during their first fall and winter if growth was slow. Of all variables tested, water temperature had the most significant impact on activity of 80 mm striped bass tested in this research. A 30% reduction in activity occurred between the maximal, 20 C value and the

lowest temperature tested, 5 C. Similar decreases in swimming ability at low temperature have been demonstrated for juvenile striped bass. Bibko, et al. (1974) demonstrated that juvenile striped bass tested at 4.4 C had lower cruising speeds than those tested at 11.1 C. Tatham (1971) found activity of juvenile striped bass at 25 C was not significantly different from activity at 22.2 C. Brett, et al. (1958) showed a 50% reduction from maximum swimming ability at upper and lower temperature limits for sockeye (O. nerka) and coho salmon (O. kisutch).

Duration of the test period had a significant effect on the activity of juvenile II striped bass. A 26% to 32% reduction of activity was observed in juveniles 80 mm long after 300 minutes of continuous swimming in this research. Bibko, et al. (1974) observed a 47% reduction in swim speed of juvenile striped bass after 180 minutes of continuous swimming. A majority of swim speed tests have been of short duration (10 to 30 min). Skinner (1974) stated that velocity was more important than length of time fish had been swimming in determining impingement susceptibility. In this study water velocity had a more significant effect on activity of juvenile striped bass than the length of time the fish had been swimming.

Tests of juvenile I and II striped bass conducted in this investigation indicated they are strongly positively rheotactic in water velocities of 15 cm/sec or more. Both

Kerr (1953) and Skinner (1974) observed strong rheotactic response in juvenile striped bass when compared with other fish species. Keenleyside and Hoar (1954) state that failure of positive rheotaxis was the expected result of fatigue in fish exposed to current. In the few impingement sequences observed in this study, juvenile bass swam positively until overcome by velocity and as repeated tail contact with the fixed screen was made orientation with respect to flow decreased. At velocities less than 15 cm/sec the rheotactic response was less pronounced in juvenile I and II striped bass. Exploritory movements made during the first 60 min of an activity period were characterized by equal amounts of positive, negative, and lateral rheotaxis. Rheotaxis, as utilized in this investigation, provided an index of behavioral response to water velocity.

Striped bass are a schooling species and schooling behavior may play a significant part in entrainment/impingement. Many of the more susceptible and valuable fish impinged on intake screens are schooling species. Larval and juvenile I striped bass observed in this research did not exhibit fully developed schooling behavior. Juvenile bass 70 to 80 mm long displayed true polarized schooling. Polarized schooling, as defined by Shaw (1970), occurred when all fish in a group oriented in the same direction and moved as a unit. In schooling fish group interaction is important and two experiments were designed to measure conspecific interaction. The effect of the number of

individuals present in the test chamber had an impact on swimming activity. Another measure of group interaction was the inter-fish distance between juvenile I striped bass at various velocities. Side-to-side spacing was shown by Cahn (1972) to be important in communication among schooling tuna, Euthynnus affinis. Breder (1965) had a different explination for inter-fish spacing. Vorticies shed from the tails of leading members of a school generate areas of microturbulence and Breder hypothesized that locomotor efficiency was increased when members of a school maintained a certain spacing.

Blind 80 mm juvenile striped bass introduced into the test chamber with sighted conspecifics demonstrated the inability of such injured fish to escape intake structures. Blind bass were unable to school. Occasionally the sighted bass would school with the blind bass for a few seconds, but the disjointed swimming pattern drove sighted fish away. Once contact was made with the side of the test chamber blind striped bass swam vigorously to maintain a position within the boundary layer, a narrow zone of reduced water velocity adjacent to tank surfaces. Longer exploratory periods displayed by blind bass may have contributed to fatigue. Repeated body contact with the screen weakened blind fish. The behavior of blind striped bass demonstrated the importance of visual cueing in schooling, response to water velocity, and avoidance of the intake screen.

When a moderately turbulent eddy was generated in the test chamber, juvenile II striped bass covered larger areas than in the absence of the eddy. The greater expenditure of energy may cause juveniles to fatigue more rapidly. Juvenile bass as a group were able to maintain an upstream orientation by rotating about the single node. If more turbulent eddies with multiple nodes were encountered it is likely that fatigue and loss or orientation would occur more rapidly. Kerr (1953) stated that turbulence was hazardous to juvenile fish and intakes should be designed to avoid turbulent areas.

CHAPTER VII

CONCLUSIONS

After examination of the swimming ability of juvenile striped bass under a variety of test conditions, it is still difficult to define the cause or synergistic causes of cooling water intake-associated fish mortality. Approach velocity does limit swimming activity in proportion to body size. Temperature, particularly low temperature, reduced swimming activity. Awareness of the simulated intake screen decreased when food was present. When the variables above were tested singly and in limited combinations, experimentally induced impingement was low. While behavioral observations of schooling and rheotaxis in the laboratory were informative, the true merit of such techniques remains in their field application where artificial conditions do not distort response.

Information obtained in this study provides many comparisons with swim speed data which often tested only a single variable under pristine experimental conditions. The value of this study is that several variables were tested simultaneously. Inclusion of variables such as the presence of food, turbulence, and injury provide a better estimate of swimming activity under natural conditions. Laboratory testing provides necessary control of variables and evaluation of a technique for field application.

As in most research, only a few of the many factors affecting swimming activity of juvenile fish could be tested. Future research to determine the effect of the presence of predators, to analyze the results of a sudden drop in temperature, and to determine the effect of turbidity on swimming activity of juvenile fish may provide valuable information on intake-associated biological damage. Preliminary work on the importance visual cueing and the impact of turbulence on activity reported in this study should be continued and expanded.

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