



Arnold Schwarzenegger  
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# VIBRATING OR FLASHING SCREENS: INVESTIGATING FISH'S ABILITY TO AVOID SCREENS AND LOUVERS USING VIBRATIONS AND STROBE LIGHTS AS DETERRENCE

PIER PROJECT REPORT

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## Preface

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For more information about the PIER Program, please visit the Energy Commission's website at [www.energy.ca.gov/research/](http://www.energy.ca.gov/research/) or contact the Energy Commission at 916-654-4878.



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## Abstract

A significant portion of California's generation capacity, approximately 45 percent, is represented by power plants located along the state's coast, estuaries, and bays that use once through cooling technology. This cooling technology requires the withdrawal of significant amounts of water and necessitates the use of screens and louvers to prevent entraining juvenile and adult fish. Louvers are slats that are arrayed perpendicular to the flow of water to guide fish movement. These screens or louvers, themselves, however can be fatal to fish if the fish contact or impinge (are trapped) on them severely or repeatedly. The importance of vision and the lateral line system in fish-screen and louver avoidance was investigated in marine and freshwater fish, including shiner surfperch (*Cymatogaster aggregata*), staghorn sculpin (*Leptocottus armatus*), steelhead trout (*Oncorhynchus mykiss*), Chinook salmon (*Oncorhynchus tshawytscha*), and Sacramento splittail (*Pogonichthys macrolepidotus*). The lateral-line system in fish are a series of cells that can detect water movement and sound and are used by fish to determine the speed, direction, and turbulence of the water surrounding their bodies and detect the location of stationary and moving objects near them in a current. Fish were viewed swimming in front of screens and louvers in large laboratory flumes. Experiments were conducted during the day (lighted) and night (dark, to limit vision). Streptomycin sulfate treatments were used to block fish's lateral line systems. The fish's lateral line system was treated with a fluorescent stain and viewed under a microscope to verify the streptomycin treatment's effectiveness. Industrial vibrators inducing near-field sound waves and a strobe light directed at the screens and louvers were tested as possible behavioral deterrents. The total number of times a fish contacted the screen or louver was analyzed as a measure of performance. All species tested contacted the screens significantly more often during the night. The response to the streptomycin, vibration, and strobe light treatments varied among species. More fish passed through the louvers than became impinged on the screens. Potential benefits of the research, along with recommendations for future experiments, are discussed.

**Keywords:** Fish screens, louvers, entrainment, impingement, lateral line system, behavioral guidance, near-field sound, strobe lights, neuromasts, DASPEI



# Executive Summary

## Introduction

An effective method of diverting or circulating water from natural systems without severely impacting populations of aquatic species must be determined to help supply California's electrical, agricultural, and residential demands. The withdrawal of large amounts of water at water intake structures can kill resident and migratory species that become entrained in the intake current. Some large-scale, freshwater diversions feature screens and louver arrays in front of their water inlet to prevent juvenile and adult fish from being displaced from their habitat. Louvers are slats that are arrayed perpendicular to the flow of water to guide fish movement. However, the screens or louvers, themselves, can be fatal to fish if the fish contact or impinge (are trapped) on them severely or repeatedly. Adding industrial vibrators or strobe lights to screens may improve the effectiveness of screen detection by nearby fishes. Also, many marine water diversions are currently unscreened, and the effectiveness of fish screens and louvers for protecting marine fishes is mostly unknown.

Fish are likely to rely on visual cues to direct their swimming during the day, but vibrations detected by the fish's lateral-line system may also play an important role in screen detection and avoidance, especially during the night. The lateral-line system in fish is composed of superficial (surface) and canal neuromasts that are sensitive to water movements and near-field sound vibrations. Neuromasts are small arrangements of hair cells that respond to motion between the fish and the water. Using the lateral-line system fish can determine the speed, direction, and turbulence of the water surrounding their bodies and detect the location of stationary and moving objects near their bodies in a current. The entire lateral-line system can be blocked by the application of the antibiotic drug streptomycin, which cleaves the hair cells from the fish making their neuromasts non-functional, to the fish's water supply. Tests can be conducted, comparing streptomycin-treated and control fish, to determine the importance of the lateral-line system in specific behaviors.

## Purpose

In California, a significant portion of California's electricity generating facilities, including hydropower and thermal power plants, divert water from the ocean, bays, streams, and rivers. These diversions pose a threat to fish and other aquatic species being swept into the intake flow. This project tested the effectiveness of fish screens and louver arrays as barriers to prevent fish being carried into water diversion intakes and to test whether increasing sound and light generated by these structures alerts fish to their presence, resulting in fewer fish-screen contacts and impingements.

## Project Objectives

The authors' objectives were to determine the sensory stimuli (such as sound or light) that different fish use to recognize the presence and threat of fish screens/louvers and to suggest new screen/louver modifications that may improve fish passage. To meet the authors'

objectives, laboratory experiments testing swimming performance and behavior were conducted on freshwater and marine fishes. Freshwater steelhead (*Oncorhynchus mykiss*), Chinook salmon (*Oncorhynchus tshawytscha*) and Sacramento splittail (*Pogonichthys macrolepidotus*) were tested in an indoor flume (an open artificial water channel) on the University of California Davis campus (Figures 1 and 2), and marine shiner surfperch (*Cymatogaster aggregata*) and staghorn sculpin (*Leptocottus armatus*) were tested in an indoor flume at the University of California Davis Bodega Marine Laboratory (Figures 3, 4, and 5). The experiments consisted of 15-minute trials where fish were observed swimming in front of either wedge-wire fish screens or louver arrays. Experimental variables consisted of light level (day vs. night), vibrations from industrial vibrators, strobe light flashes, and streptomycin treatments. The combinations of these treatments used varied with the species tested. To determine if the streptomycin treatments were effective at blocking the fishes' lateral-line system, treated and control fish were stained with 2-(4-[dimethylamino]styryl)-N-ethylpyridinium iodide and viewed under a fluorescent microscope.

### **Project Outcomes**

The streptomycin sulfate treatments proved to be effective in destroying most of the fish's neuromasts when the dosage was sufficiently high. The general outcome was that all the fish contacted the screens more frequently at night and were more likely to become permanently impinged on the screen at night. In the nighttime trials, a higher percentage of fish passed through the louver arrays than became permanently impinged on the screens. Results varied significantly among the different species and treatment groups tested and are discussed below.

### **Conclusions**

Fish contacted the screen and louvers in every set of experiments indicating that if a barrier was not in place, most fish would have been drawn through the simulated diversion. The reason that most fish contacted and impinged on the screen and louvers less frequently during the day is probably because they were using visual cues, which were not available at night, to perceive the screen and avoid it. During night fish were commonly observed drifting back toward the screen and then swimming just before they came in contact with it. These observations indicate that either the fish were able to detect the screen at night, through their lateral-line system or sensitive low-light vision, or they had learned the screen's location by remembering where they contacted it earlier in the trial.

At an adequately high dose, streptomycin sulfate was found to destroy the majority of neuromasts for all tested species. The increased screen contact rates seen in the splittail and surfperch treated with streptomycin during the nighttime indicated that their lateral-line system sensory inputs assisted these fish in avoiding the screen. The other two species apparently use their lateral-line systems to lesser extents, while avoiding screens.

The shiner surfperch and staghorn sculpin showed a significant decrease in contacts with the screen when it received low-frequency impacts from the vibrator (like a large hammer hitting the screen every 1.5 seconds). The fish would commonly burst-swim forward into the current and away from the screen every time the vibrator struck at the start of the trials. These results

indicate that low-frequency, near-field vibrations can help repel some marine fish from contacting screens. Interestingly, the vibrating screens were mostly ignored by fish in the freshwater treatments, probably because the vibrators used in these trials all ran at sound frequencies that were out of the target range of 10-15 hertz that may repel fish. Also, the marine louvers frequently allowed the fish to pass through them on their first approach.

In the strobe-light treatments, staghorn sculpins actively swam away from the lighted screens and louvers shortly after coming to rest on them and sometimes before they made contact, showing that strobe lights may make an effective deterrent for this species. However, surfperch and steelhead actually contacted the screens more frequently during nighttime trials while flashed by the strobe light. Thus, more research is required before making conclusions about the most effective combination for repelling coastal fish communities from water intakes.

### **Recommendations**

The experiments indicate that fish screens and louver arrays placed in front of water diversions may allow fish to potentially escape entrainment. Fish avoided contact with screens and louvers to a greater extent during the day than night, which suggests that pumping should be reduced during the nighttime. The findings show that different fish species rely on both visual and sound cues, to different degrees, to detect and avoid physical barriers while swimming in a current. Vibrating devices that emit low-frequency, strong near-field vibrations may have potential at repelling fish, but further testing is needed (preferably with a device that vibrates in the 10-15 hertz range) before any general statements can be made. Strobe lights may also be an effective deterrent, but the fish must have a space to swim to, away from the flashes, to make them effective. Behavioral guidance devices directed at either sensory system can be effective at guiding fish away from hazards, but they may only be effective under certain conditions (for example, nighttime) or for certain species. Installing screens to prevent fish passage may be desirable vs. louvers, but louvers are preferable for fish protection vs. an open (that is, unscreened/louvered) diversion.

### **Benefits to California**

The results of this project can help to minimize potential impacts of water diversions on wild and hatchery fish populations. Fish screens are the current solution for protecting fish from numerous water diversions in California. Therefore, any increase in these screens' effectiveness should substantially assist California's fish populations and lessen the impacts of electric power generation and other practices that require water extractions. The findings from this project will help direct future research in designing an effective, close-proximity fish-screen deterrent.

**Note:** Unless otherwise indicated, all graphics in this report are the outcome of the research described herein.



# 1.0 Introduction

## 1.1. Background and Overview

An effective method of diverting or circulating water from natural systems without severely impacting populations of aquatic species must be determined to help supply California's electrical demands, as well as those needed for agricultural, and residential uses. The withdrawal of large amounts of water at water intake structures can be lethal to residential and migratory species that become entrained in the influent current. Screens and louver arrays can be mounted in front of the inlets at large water diversions to prevent juvenile and adult fish from being displaced from their habitat, but the screens themselves can be fatal to fish if they impinge on them severely or repeatedly. Louvers are commonly used to guide fish toward a bypass or collecting area, but in this study we tested them as an alternative for a physical barrier screen with only reverse escapement available for the fish by swimming against the current. One potential method to improve the effectiveness of fish screens and louvers is to modify them in a manner that will make their presence widely apparent, providing fish the greatest chance of avoidance. Also many marine water diversions are currently unscreened, and the effectiveness of fish screens and louvers in protecting marine fishes is mostly unknown. California's water demands are expected to increase in the near future, increasing the threat of entrainment-related losses for many aquatic animals. Increasing the ability of fish screens and louvers to deter aquatic animals with minimal contact may help to minimize the current and future impacts of water diversions on California's fish populations.

To pass a fish screen without contact, fish must be able to detect the screen's presence, perceive that contact with it is imminent and threatening, and have the physical ability to avoid the screen. All fish use the same sensory systems to monitor their surroundings and maintain a regular swimming position, but the sensitivity and importance of different systems can vary between species or under different conditions. The sensory systems guiding screen avoidance behaviors are likely vision and mechanoreception. Vision is important to screen detection, because fish commonly use it to maintain their swimming positions and to recognize obstructions in the water column (Herman et al. 1996, Kynard et al. 2001). Visual capabilities greatly vary among different fish species (Kusmic et al. 2000) and are less useful at night or in turbid conditions, stressing the significance of mechanoreception. Mechanoreception allows a fish to detect movements and vibrations in the water surrounding its body, by using its lateral-line system. The lateral line functions by detecting the presence, velocity changes, and strength of water flows, which can be as important to swimming orientation as gravity and light (Montgomery et al. 2000). It is used by some fish species to detect structures (Montgomery et al. 2001), avoid predation (Canfield and Rose 1996), maintain school formations (Pitcher and Perrish 1993), and orient to water flows (Bleckmann 1993). Differences in sensory capabilities among species are, theoretically, the result of evolution to different habitats (Kusmic et al. 2000, Montgomery et al. 1993) and may govern the species' abilities to detect and avoid fish screens.

This project assessed the effectiveness of fish screens and louver arrays as fish barriers placed in front of water diversions, and it tested the hypothesis that increasing the stimuli (visual or mechanosensory) generated by these structures will alert the fish to their presence and result in fewer fish contacts with them. Our objectives were to determine the sensory stimuli that

different fishes use to recognize the presence and threat of fish screens and to suggest new screen modifications that may improve fish avoidance and passage.

## **1.2. Lateral Line System**

The lateral line system is comprised of superficial and canal neuromasts and both may contribute to fish screen detection and avoidance. Superficial neuromasts are concentrated in freestanding cupulae that project outward from a fish's body. Cupulae are friction coupled to the water column, causing them to tilt as water moves across a fish's body. As the cupulae tilt they stimulate neuromast hair cells causing an increase or decrease in an ongoing neuronal response to the fish's brain, depending on the direction the hair cells are bent (Engelmann et al. 2002). Superficial neuromasts are most sensitive to low frequency disturbances (<1 – 30 Hz) (Montgomery et al. 2002). By integrating numerous neuromasts, which are sensitive to displacements in different directions, a fish can determine the speed, direction, and turbulence of the water surrounding it, allowing it to perform rheotaxis and other important swimming behaviors (Voigt et al. 2000, Carton and Montgomery 2002).

Canal neuromasts innervate the same section of a fish's brain as superficial neuromasts, but have evolved to determine acceleration in water currents and the locations of moving objects in the fish's vicinity. Canal neuromasts are located beneath the fish's skin in bony canals or tubes through the scales that open to the water through a series of small pores. Canal neuromasts commonly detect higher frequency wavelengths (30-200 Hz), and are shielded from stimuli generated by constant water velocities (Montgomery et al. 2002). Therefore canal neuromasts can detect wavelengths from external sources equally well in still and flowing water, such as vibrating spheres and possibly vibrating screens. Superficial neuromasts show greater responses to vibrating spheres than canal neuromasts in still water, but almost no response when there are currents across the skin (Engelmann et al. 2002, Krother et al. 2002).

Researchers have used antibiotics to pharmacologically ablate fishes' lateral-line systems and investigate its role during specific behaviors. The entire lateral-line system can be blocked by the application of streptomycin to the fish's water supply (Blaxter and Fuiman 1989). This treatment cleaves the hair cells from the fish's neuromasts making them non-functional, and has been confirmed by scanning electron microscopy. Fish subjected to this treatment lose the ability to orient to low-velocity water flows and to locate external vibrating stimuli (Montgomery et al. 1997, but see Janssen 2000). Behavioral studies conducted in this manner have many advantages. 1. They commonly yield responses at lower thresholds than found in studies using electrophysiological readings of afferent neurons (Montgomery 2000). 2. They only affect fish temporarily, because cleaved hair cells in fish grow back after a few weeks. 3. They are performed with free-swimming fish allowing otherwise natural behaviors during specific activities, including encountering a fish screen or louver array while swimming in a current.

## **1.3. Behavioral Studies**

Experiments blocking specific sensory systems can be used to understand the contributions of vision and mechanoreception during screen or louver recognition and avoidance. Fish can be tested in both light and dark conditions to determine the contribution of vision. Many fish

species are known to contact screens less frequently and less severely under lit conditions (Swanson et al. 2004, 2005), suggesting that visual recognition of screens is a limiting factor in screen detection. To test the contribution of the lateral-line system, streptomycin sulfate can be used to temporally block mechanoreception and allow observation of otherwise natural behavior. It may be possible to enhance a screen's or louver array's detectability by increasing the amount of stimuli they generate. Implementing artificial lighting or vibration generators along screens or louvers might increase fishes' ability to detect them or recognize them as threatening, and provide safer passage. Previous experiments using infrasound and flashing strobe lights to behaviorally deter fish from hazardous areas in natural environments have found mixed results. Experiments conducted in lakes, net pens and laboratory settings have shown that juvenile salmon swim away from strobe lights set at 300 flashes per minute at night (Maiolie et al. 2001, Ploskey & Johnson 2001, Muekker et al. 2001). Another strobe light experiment found that salmon avoid strobe lights during the day, but steelhead show no response (Taft et al. 2001). Juvenile salmon have also shown very strong avoidance to speakers broadcasting different wavelengths of infrasound in some experiments (Sand et al. 2001), but no significant avoidance in others (Goetz et al. 2001).

The behavioral warding devices used in this experiment were different from those used in most of the previous studies, which attempted to use intense sensory stimuli generated by small non-threatening objects to deter fish. The industrial vibrators and strobe lights used in this study increased stimuli generated by the screens or louvers themselves, which are large, and probably threatening objects in the environment. Fish will naturally avoid contact with screens when possible (Swanson et al. 2004, 2005). Fish may show a stronger avoidance response to vibrating screens or louvers generating (near-field) particle accelerations that are a proximal and directional threat, compared to distant (far-field) pressure waves that are generated by speakers. Near-field infrasound has been shown to deter fish from one side of a stream to the other in the wild (Sand et al. 2001). The goal of this experiment is to determine methods that will enhance the detectability and perceived threat level of fish screens and louver arrays, providing fish the greatest chance at passing them without contact. It is possible that enhancing the screen's detectability may increase other natural dangers that small fish face in the habitat. Visual piscivores may aggregate in areas with increased illumination, or become more effective at capturing prey. Different species detect light wavelengths and vibration frequencies with different levels of acuity, so it may be possible to isolate stimuli that would increase the detectability of the fish screen to vulnerable species and be of little use to other species of predatory fish.

#### **1.4. Project Objectives**

The importance of the lateral-line sensory system in fish-screen recognition and avoidance is mostly unknown, yet this system may be the most important sense in allowing a fish to detect and avoid fish screens and louver arrays, especially in dark and light-limited (e.g., highly turbid) conditions. This study is the first that compares the effectiveness of wedge-wire fish screens and louver arrays at preventing the passage of marine fish through water diversions. The results of this experiment can help to minimize potential impacts of fish screens on natural fish populations. The screen modifications studied in this experiment can be added to existing screens or louvers if they are determined to be significantly beneficial.



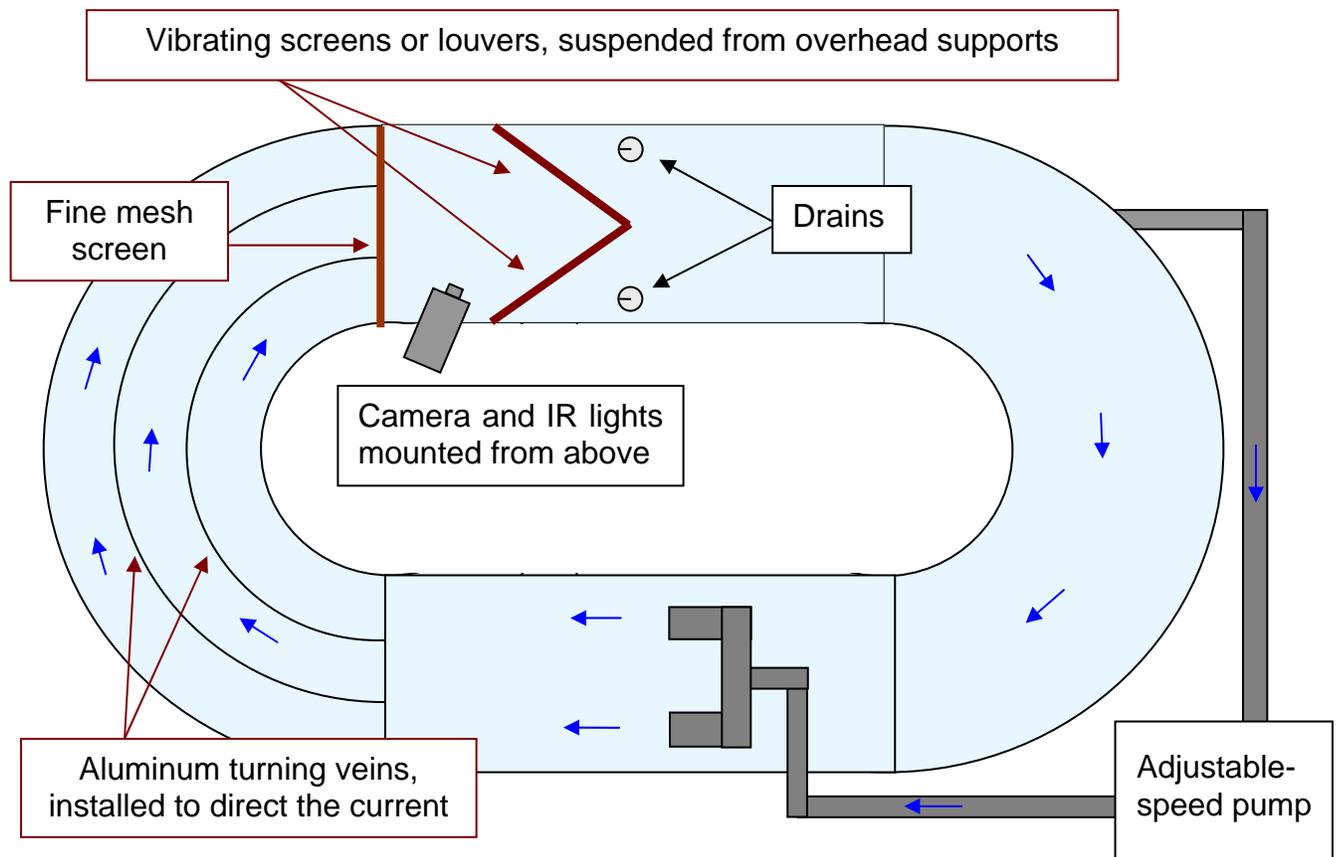
## 2.0 Methods

### 2.1. Freshwater Species

Research on freshwater species was conducted at the Center for Aquatic Biology and Aquaculture (CABA) on the UC Davis Campus. Juvenile steelhead (*Oncorhynchus mykiss*) and Chinook salmon (*Oncorhynchus tshawytscha*) were reared and received from the Nimbus Fish Hatchery. Sacramento splittail (*Pogonichthys macrolepidotus*) were received from the Tracy Fish Facility where they had been salvaged from water-pumping operations. Fish were transferred to CABA in heavy-duty, polyethylene bags, which were filled with water from the facilities and incorporated an oxygen atmosphere above the water, and were situated in insulated coolers. At CABA the fish were housed in flow-through, aerated, and temperature-controlled tanks where they were fed and maintained daily.

### 2.2. Freshwater Flume Design

A custom, fiberglass swimming chamber (flume) was designed and constructed with the assistance of D&T Fiberglass (Sacramento). The flume was located indoors and was 25 feet long, 10.5 feet wide and 3 feet deep, with a 3-foot-wide, 3-foot-deep channel. A 7.5-horsepower, 320-volt, GOULDS pump was installed with an Automation Direct variable frequency drive (VFD), to vary the pump's speed. Two stainless-steel, wedge-wire, fish screens (3 ft by 3 ft) were suspended over one of the flume's straight channels. The screens were positioned in an equilateral triangle shape, starting at the walls and meeting in the middle of the flume, the point directed downstream (Figures 1 and 2). The hanging screens were not attached to the chamber so that vibrations from the screens would not be transferred directly to the chamber. Plastic mesh was added around the sides and base of the screens to prevent fish from swimming past them. A screen made of one-quarter-inch stainless-steel mesh on a steel frame, was added, upstream of the wedge-wire screen. This created a trapezoid-shaped, enclosed section of the flume where the fish would swim. This configuration exposed the fish to contact with the wedge-wire screens if it drifted backwards in the flume during swimming trials, but it allowed for an open area ahead of these screens where it could swim to avoid contact. Water was extracted from drains behind the screened area and pumped back into the tank through inlet jets on the opposite side of the chamber. Initial trials found that the water velocity was much greater along the outer walls of the flume. Therefore aluminum turning vanes were installed at the curved end of the flume, upstream of the screens, to distribute the flow evenly across the wedge-wire screens. The water depth was maintained at 30 cm and the temperature was maintained at 13°C.



**Figure 1. Top-view diagram of the freshwater flume, showing the water current's direction. (Approximate dimensions: 8m long, 3m wide, 1m deep, and 1m wide channel)**



**Figure 2. Pictures of the freshwater flume; left: a picture of the entire flume; right: a close-up picture of the wedge-wire fish screens and a steelhead in fish-swimming area.**

Industrial pneumatic, piston-driven vibrators were bolted to each of the wedge-wire screens to produce strong vibrations along the entire screen. Different vibrators were used over the course of the study when models producing vibrations closer to the target range of 12 Hz were acquired. Most small-sized industrial vibrators run at high frequencies (>100Hz) and many models were tested that had the potential of running at slow speeds. Only the final study with Chinook salmon used a vibrator that produced the target frequency. The vibrators were attached in the middle of the screens above the water level. Only one screen was vibrated at a time with the vibrating side being chosen randomly for every set of experiments. A strobe light (Monarch Stroboscope) was mounted above and in front of the screens with the flashes directed down and back at the screens. The strobe light emitted 300 flashes per minute, with a short flash duration of 20-50  $\mu$ sec and flash energy of 220 mJoule.

A Sony Handycam camera (Model DCR-DVD505) was suspended from the ceiling above the swimming area and recorded the daytime and nighttime trials on a VCR, allowing subsequent and detailed analysis of the fishes' behaviors. The cameras "Night-Shot" function, combined with two infra-red LED flood lights installed over the chamber, allowed the fish to be viewed with infra-red light during swimming trials in the dark. A clear Plexiglas view plate was designed and constructed to float on the surface of the water so the fish's behavior could be viewed through the moving water clearly. The view plate was attached with nylon cord to the fine mesh screen so that it floated 2 cm in front of, but not touching, the wedge-wire screens. This allowed the screens to vibrate without transferring vibrations to the view plate. Night-vision goggles were used at night when loading and retrieving fish from the flume. Therefore, fish swimming in nighttime experiments were loaded into the flume in the dark.

## **2.3. Freshwater Swimming Trials**

Individual fish were held in aerated, temperature controlled, 5-gallon buckets for 24 h before their swimming trial. Half of the buckets were treated with streptomycin sulfate and the others left without chemical treatments (control). Individual fish were placed into the flume during daytime (lighted) or nighttime (dark) and given a  $60 \pm 10$  min-acclimation period. Following acclimation, the stimulus on the screen was started (if appropriate to the experiment) and a water velocity of 0.5 m/sec was started in the flume. The fish's swimming performance was observed and recorded for 15 min. After the trial was completed, fish were euthanized in MS-222 (0.5 g/l), their size and weight were measured, and their general health was assessed by inspecting the fish for physical injuries or deformities. Fish were tested individually and only used once. Videos were analyzed to determine: 1. the total number of times the fish contacted the screens, 2. if the fish had permanently impinged on the screen during the trial, and 3. the fish's location and general behavior during the experiment.

### **2.3.1. Steelhead Experiments**

The first set of steelhead experiments were investigated for a previous PIER project (Cech & Mussen 2006) and comprised 8 different treatment combinations with 8 fish (13.7 cm [ $\pm$  0.15 SEM] average total length, and 23.9 g [ $\pm$  0.76 SEM] average mass) tested in each. The treatments included streptomycin sulfate (0.11 g/l), screen vibrations (Houston BV-150 vibrator, 65Hz), a combination of streptomycin and vibrations, and control treatments during both day and night trials. A second set of steelhead experiments was conducted during the night for this project,

and was comprised of 6 different treatment combinations with 4 fish tested in each (10.1 cm [ $\pm$  0.34 SEM] average total length, and 10.6 g [ $\pm$  0.82 SEM] average mass). The treatments included streptomycin sulfate (0.20 g/l), screen vibrations (B.E.S. Inc. FP-35-L vibrator, 45Hz), strobe light illumination (Monarch Stroboscope, 300 flashes/min) a combination of streptomycin and strobe light flashes, a combination of streptomycin and vibrations, and a control treatment. The results were analyzed statistically using a three-way ANOVA with a Poisson distribution (SAS 9.13 software) The Poisson distribution is very effective at comparing differences in small sample sizes and count based data. Tukey's post hoc test was used to identify significant differences in total numbers of tail touches between treatments at ( $\alpha = 0.05$ ).

### **2.3.2. Splittail Experiments**

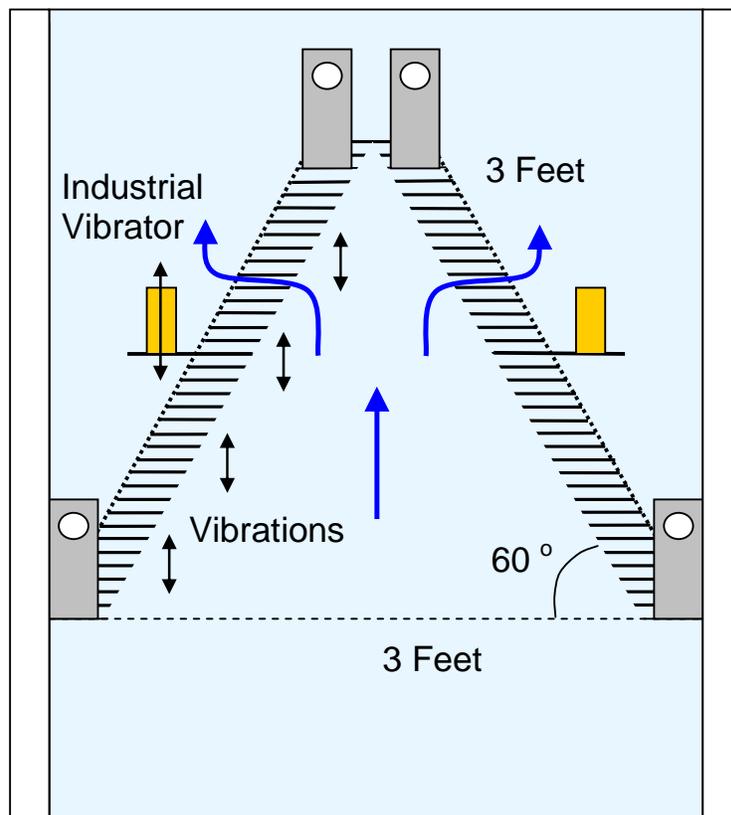
The first splittail experiments were comprised of 8 different treatment combinations with 10 fish tested in each (12.3 cm [ $\pm$  0.12 SEM] average total length, and 14.0 g [ $\pm$  0.52 SEM] average mass). The treatments included streptomycin treatments (0.20 g/l), screen vibrations (B.E.S. Inc. FP-35-L vibrator, 45Hz), a combination of streptomycin and vibrations, and control treatments during both daytime and nighttime trials. A second set of splittail experiments, conducted during the night, was comprised of 6 different treatment combinations with 4 fish in each (13.0 cm [ $\pm$  0.29 SEM] average total length, and 16.6 g [ $\pm$  1.14 SEM] average mass). The treatments included streptomycin sulfate (0.20 g/l), screen vibrations (B.E.S. Inc. FP-35-L vibrator, 45Hz), strobe light illumination (Monarch Stroboscope, 300 flashes/min) a combination of streptomycin and strobe light flashes, a combination of streptomycin and vibrations, and a control treatment. Because the results were similar for the two sets of experiments, the data were pooled for analysis. The results were analyzed statistically using a three-way ANOVA with a Poisson distribution (SAS 9.13 software). Tukey's post hoc test was used to identify significant differences in total numbers of tail touches between treatments at ( $\alpha = 0.05$ ). Fisher's exact test was used to determine significant differences between treatments, regarding the percentages of fish that were permanently impinged on the screens.

### **2.3.3. Chinook Salmon Experiments**

Chinook salmon were tested swimming in front of louver arrays instead of screens. The experiments investigated 5 different treatment combinations including a daytime control, nighttime control, nighttime vibrations (Martin NTK 25, 0.11Hz), nighttime strobe light flashes (Monarch Stroboscope, 300 flashes/min) and nighttime streptomycin (0.5g/l) at 4 different water velocities (0.30, 0.65, 0.98, and 1.30 ft/s). The 4 velocities were tested to determine if there was a threshold velocity for fish passage through the louvers and to determine the effectiveness of vibrations or strobe lights at repelling fish at different velocities. The Chinook salmon's average total length was (14.5 cm [ $\pm$  1.3 SEM] and average mass was 31.5 g [ $\pm$  2.9 SEM]). Fish were tested individually and only used once, with the sample size in the treatments ranging over 3 to 10 fish. More fish were tested at faster flows where they were more likely to pass through the louvers as shown in figure 14.

The louvers were constructed by Twisted Metal (Sacramento) and had the same height (3 ft) and width (3 ft) as the wedge-wire screen. Each louver had 37, vertical 2.5-inch-wide slat arrays that were 1/8 inch thick; with each slat spaced one inch apart and attached at 60° so they were oriented perpendicular to the current (Figure 3). An extension was mounted on the back of the

middle louver slat allowing the vibrator to be attached. The mild steel louvers were painted in a gray-colored, rust-resistant paint (Rust Bullet) prior to being used in the experiments to help prevent chemical deterioration/leaching (e.g., rusting). The louvers were suspended in the flume in the same configuration as the screens and had plastic mesh added on their sides and base so the fish could only pass them by traveling between the louver slats. The fish were given no acclimation time in the trials, because of the large (much larger area than in the screen trials) open area (9 m of flume channel) where the fish could swim ahead of the louvers and were released into the flume from a fish net with the water flowing. The results were analyzed statistically using a three-way ANOVA with a Poisson distribution (SAS 9.13 software). Tukey's two-way post hoc test was used to identify significant differences in total numbers of tail touches within and between treatments and water velocities ( $\alpha = 0.05$ ). Fisher's exact test was used to determine significant differences between treatments, regarding the percentages of fish that were permanently impinged on the screens.



**Figure 3. Diagram of the louver arrays showing vibrations (black arrows) being produced from the left-side louvers and the saltwater current's movement (blue arrows) through the louvers in the flume.**

## 2.4. Marine Species

Shiner surfperch (*Cymatogaster aggregata*), and staghorn sculpin (*Leptocottus armatus*), were collected using a 30-ft seine in the channel of Bodega Harbor (2008 California Collecting permit #803017-01), and transported in aerated, insulated coolers to the UC Davis Bodega Marine Laboratory (BML). All other species collected in the seine were immediately returned to the water. Unfortunately, the young-of-the-year topsmelt (*Atherinops affinis*) and jacksmelt

(*Atherinopsis californiensis*) collected in the seine were too small to survive the transport back to the laboratory. Therefore these fish were released when captured. Collected fish were held in aerated tanks with flow-through seawater, fed frozen brine shrimp and live mysid shrimp, and maintained daily. These species were selected because they are common near-shore species in Bodega Harbor and are typical species in many, sub-tidal coastal-California habitats (Love 1996).

## **2.5. Marine Flume Design**

Due to time and space limitations a second recirculating swimming chamber (flume) was built for experiments incorporating marine fishes in an indoor wet lab at the UC Davis Bodega Marine Laboratory (Figures 4 and 5). The flume was constructed from an existing 12-ft long by 4-ft wide by 3-ft deep fiberglass tank at the laboratory. Plastic walls were installed on the sides of the chamber to make the flume 3 ft wide, and a plastic middle partition was installed horizontally so water would circulate between the top and bottom of the flume if a current was started. Strips of plastic bent into a half circle were installed at each end of the chamber to help direct the current. Two Hitachi Minn Kota electric trolling motors were used to generate the current. They pushed water from the bottom of the flume around the plastic bend and to the top, so that the flow would be relatively even in the fish's swimming area on the top. The top portion of the flume closely resembled the swimming area used in the freshwater experiments. Wedge-wire screens were suspended at one end of the flume in the same manner as the freshwater experiments so that they did not contact the chamber or each other. On the other end of the flume from the wedge-wire screens, a plastic mesh was attached across the chamber restricting the fish's movements to the viewing area and providing an area fish could swim into, to avoid the screens. Plastic mesh was also attached to the sides and base of the wedge-wire screens to prevent the fish from leaving the view area. The water depth was 30 cm in the chamber, and the water temperature averaged 10°C. The lighting, view plate, and video equipment were the same as those used in the freshwater studies. A Martin PKL 150 single-impacting vibrator, which produced loud impacts on the screen at about 0.75 Hz, was used in the marine trials. Streptomycin sulfate was used at 0.5 g/l in the marine studies, because this dose was shown to be effective in previous studies (Montgomery et. al. 1997).

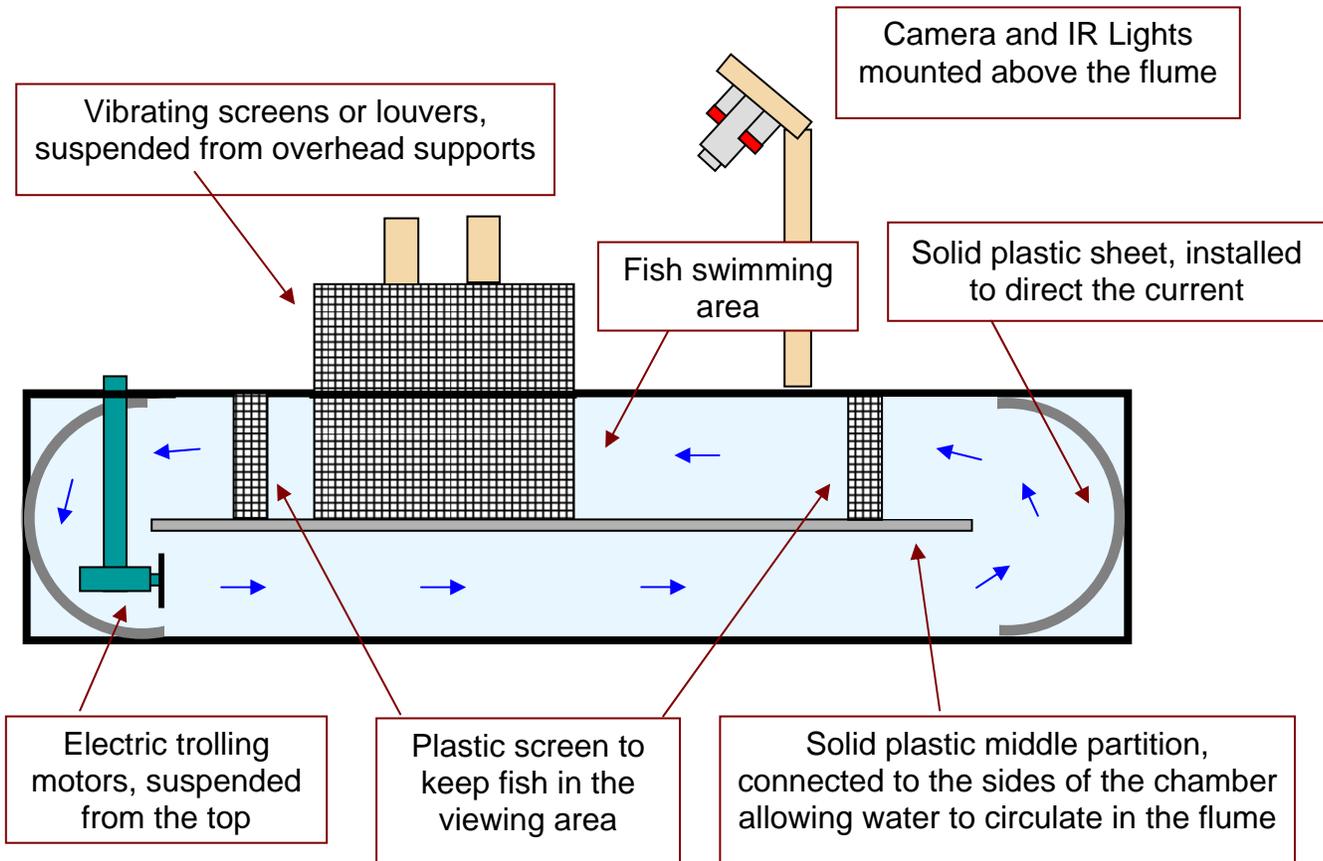


Figure 4. Side-view diagram of the saltwater flume, showing the current's direction. (Approximate dimensions: 14m long, 1m wide, and 1m deep)



Figure 5. Pictures of the saltwater flume; left a picture of the entire flume; right a close up of the louver arrays and the fish swimming area.

## 2.6. Fish Screen Experiments With Surfperch and Sculpin

Screen avoidance swimming trials were conducted with 67 shiner surfperch (10.7 cm [ $\pm$  0.24 SEM] average total length, and 17.1g [ $\pm$  1.21 SEM] average mass) and 25 staghorn sculpin (8.5 cm [ $\pm$  0.27 SEM] average total length and 6.9 g [ $\pm$  1.04 SEM] average mass) using the wedge-wire fish screens. The experiments investigated 5 different treatment combinations including a daytime control, nighttime control, nighttime vibrations (Martin PKL 150, 0.75Hz), nighttime strobe light flashes (Monarch Stroboscope, 300 flashes/min) and nighttime streptomycin (0.5g/l). Five fish were held in individual, aerated 5-gallon buckets filled with 8 l of seawater and placed in a flow-through ambient seawater bath to maintain proper water temperature for 24 hours prior to experimentation. One bucket contained streptomycin sulfate and the other four were chemical free. Fish were transferred from their bucket to the swimming chamber in nets using infrared goggles in the dark. They were given a 60 $\pm$ 10-min acclimation period. Following acclimation, the stimulus on the screen was started (if appropriate to the treatment) and a water velocity of 0.3 m/s was started in the flume. The fish's swimming performance was observed and recorded for 15 min. After the trial was completed, fish were euthanized in MS-222 (0.5 g/l), their size and weight were measured, and their general health was assessed by inspecting the fish for physical injuries or deformities. Fish were tested individually and only used once. The videos were analyzed as previously described. The results were analyzed statistically using a one-way ANOVA test with a Poisson distribution (SAS 9.13 software). Dunnet's post hoc test was used to identify significant differences between the nighttime control group and the other treatments at ( $\alpha$  = 0.05). Fisher's exact test was used to determine significant differences in the percentages of fish that passed through the louvers between treatments.

## 2.7. Louver Array Experiments With Surfperch and Sculpin

Following the screen-avoidance experiments, a series of swimming trials was conducted using louver arrays to determine their relative effectiveness at preventing marine fish from becoming entrained into simulated water diversions. The louver-avoidance behavior of 22 shiner surfperch (10.5 cm [ $\pm$  0.45 SEM] average total length, and 19.0 g [ $\pm$  2.4 SEM] average mass) and 39 staghorn sculpin (7.2 cm [ $\pm$  0.24 SEM] average total length, and 4.40 g [ $\pm$  0.55 SEM] average mass) was tested in the flume at a slower velocity of 0.2 m/sec, allowing the fish a greater chance to avoid the structure. The louvers were suspended in the flume in the same configuration as the screens as described in the freshwater studies. The fish were given no acclimation time in the trials and released into the flume from a fish net with the water flowing. Fish were tested individually and only used once. The treatments tested included nighttime control, nighttime strobe light flashes (Monarch Stroboscope, 300 flashes/min), nighttime vibrations (Martin PKL 150, 0.75Hz), and daytime control (no daytime control treatment was tested for shiner surfperch). The trials ended after 15 min or when the fish passed through the louvers. After the trial was completed, fish were euthanized in MS-222 (0.5 g/l), their size and weight were measured, and their general health was assessed by inspecting the fish for physical injuries or deformities. Results were analyzed statistically using a one-way ANOVA test with a Poisson distribution (SAS 9.13 software). Dunnet's post hoc test was used to identify significant differences between the nighttime control group and the other treatments ( $\alpha$  = 0.05). Fisher's exact test was used to determine significant differences in the percentage of fish that passed through the louvers between treatments.

## 2.8. DASPEI Staining Techniques

To determine the dose of streptomycin sulfate required to eliminate lateral-line function, dose-response tests were performed. For the splittail and steelhead four fish were tested at each concentration of streptomycin sulfate for 24 hours. The fish were held in individual, aerated containers and subjected to either control (0.0 g streptomycin/l) or to one of five streptomycin treatments (0.1, 0.2, 0.3, 0.4 and 0.5 g streptomycin/l). Fish were then placed in aerated water with 1 mmol/l (0.5 g/l) of 2-(4-(dimethylamino)styryl)-N-ethylpyridinium iodide (DASPEI) for 20 minutes, to make their neuromast cells visible under a fluorescent microscope (Engelmann et al. 2002). The fish were viewed with a Leica MZFLIII Stereomicroscope fitted with a "blue" filter set (with Excitation at 450-490 nm and emission with a long pass over 510 nm). The lowest concentration of streptomycin that removed all hair cells, thus blocking the fish's ability to detect vibrations, was used in the subsequent swimming studies. Unfortunately this technique was started after the early tests on steelhead were completed, so they were tested with a lower dose of streptomycin (0.11g/l) than was needed for optimal effect. Because there was no access to a fluorescent microscope at the marine laboratory, and seawater is known to lessen the effects of streptomycin, a 0.5g streptomycin/l dose was used in the surfperch and staghorn trials. This dose has been effective at blocking the lateral-line systems of other marine fish (Montgomery et al. 1997). The dose was also determined to be effective by comparing DASPEI stained fish treated with 0.5g streptomycin/l and DASPEI stained control fish under a fluorescent microscope at a later date.



## 3.0 Results

### 3.1. Results of DASPEI Staining

The 24 hour streptomycin sulfate treatments proved to be effective in destroying most of the fish's neuromasts when the dosage was sufficiently high, including in the marine species at the BML, where a fluorescent microscope was not immediately available. Figures 6, 7, 8, 9 and 10 show control (untreated fish) compared to fish treated with streptomycin for every species investigated.

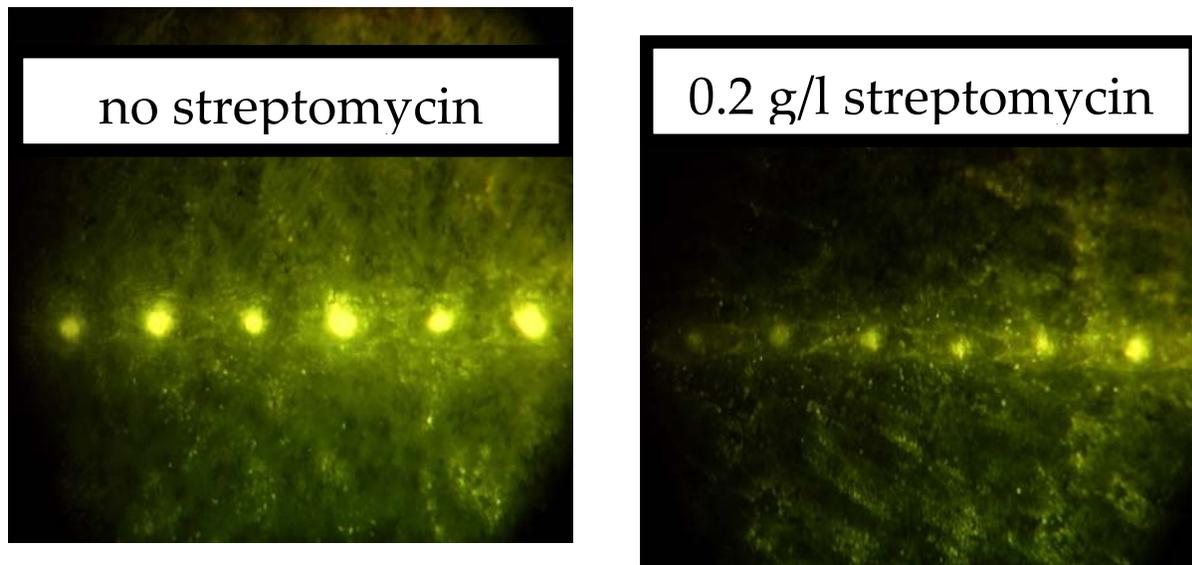


Figure 6. Steelhead trunk lateral line neuromasts treated with DASPEI at 5.0X magnification, showing a control fish that received no streptomycin treatment (left) and a fish that treated with a 24-h exposure to 0.2 g/l streptomycin (right).

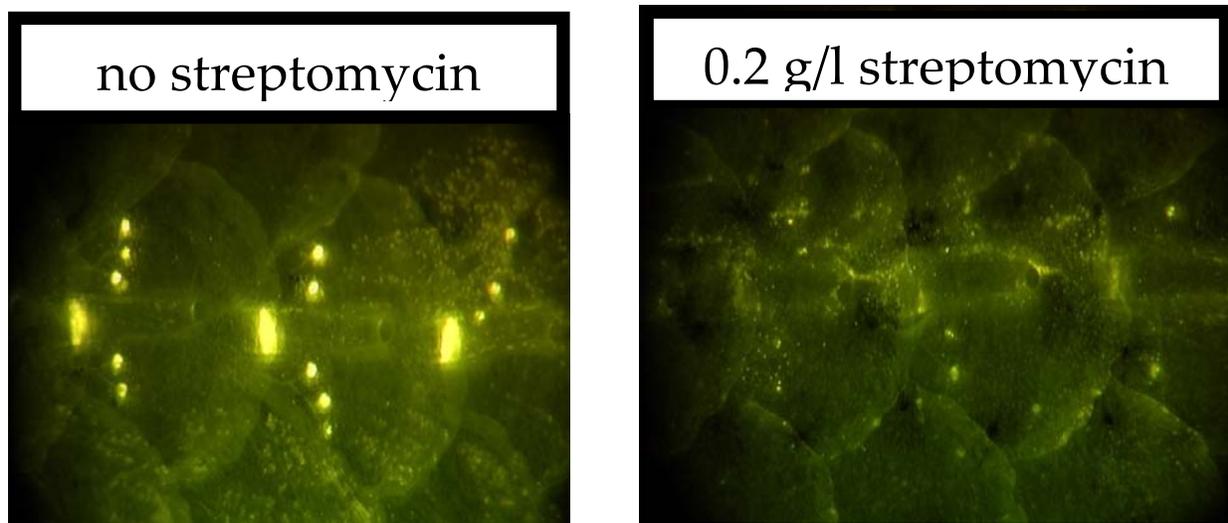
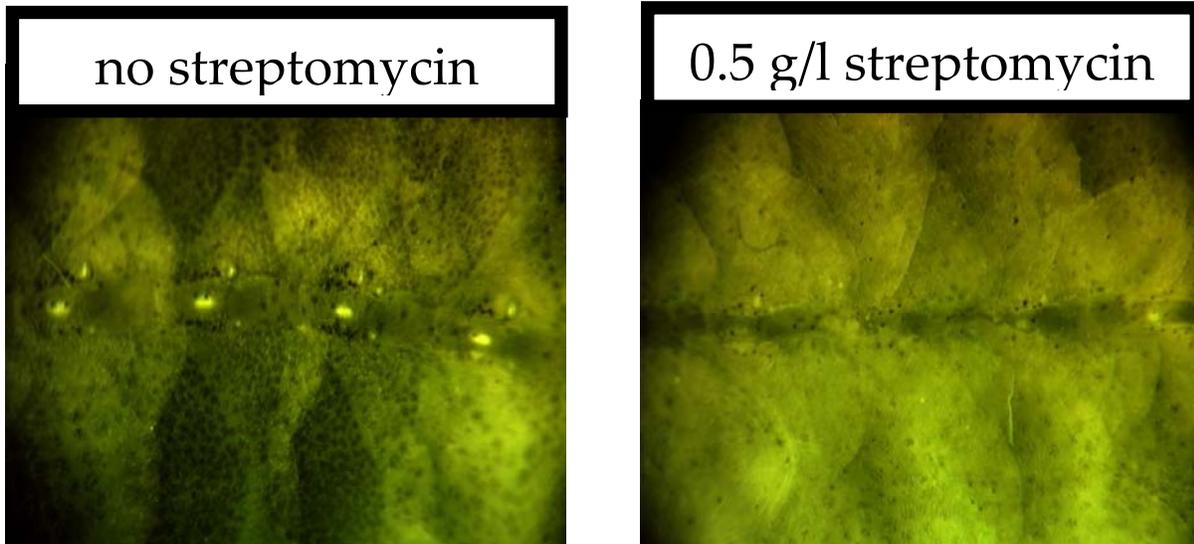
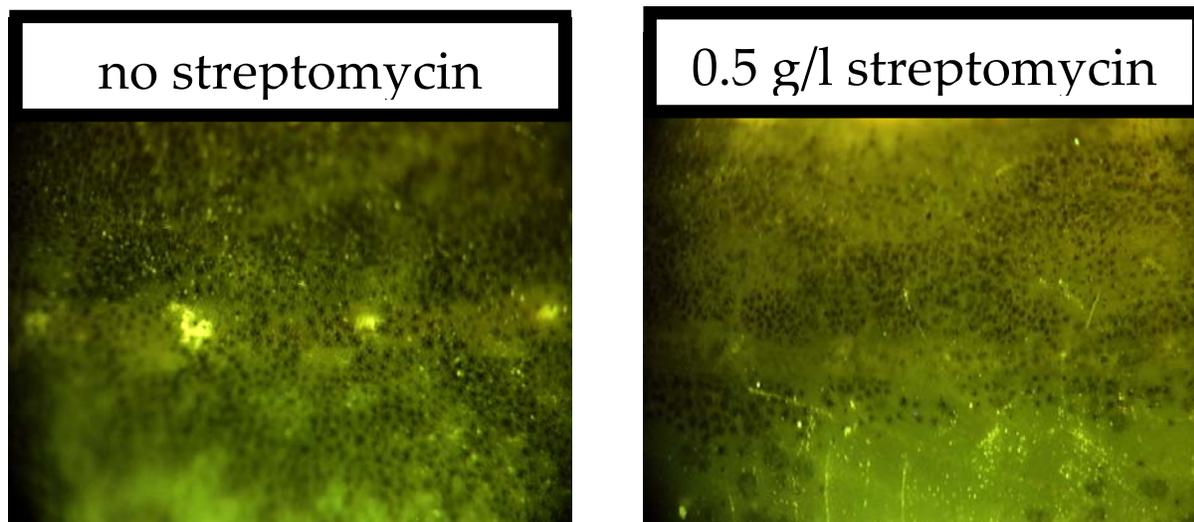


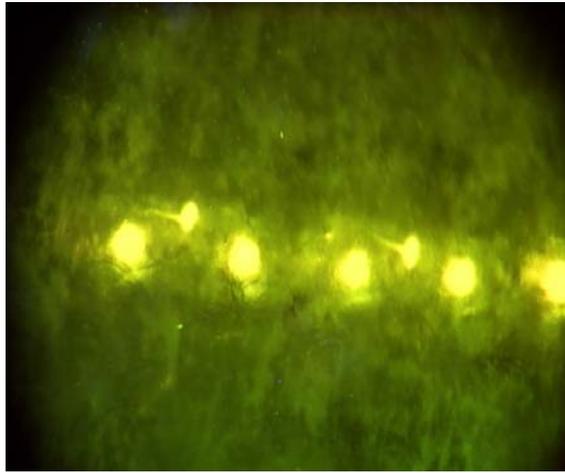
Figure 7. Splittail trunk lateral line neuromasts treated with DASPEI at 5.0X magnification, showing a control fish that received no streptomycin treatment (left) and a fish that treated with a 24-h exposure to 0.2 g/l streptomycin (right).



**Figure 8.** Shiner surfperch trunk lateral line neuromasts treated with DASPEI at 2.5X magnification, showing a control fish that received no streptomycin treatment (left) and a fish that treated with a 24-h exposure to 0.5 g/l streptomycin (right).



**Figure 9.** Staghorn sculpin trunk lateral line neuromasts treated with DASPEI at 2.5X magnification, showing a control fish that received no streptomycin treatment (left) and a fish that treated with a 24-h exposure to 0.5 g/l streptomycin (right).



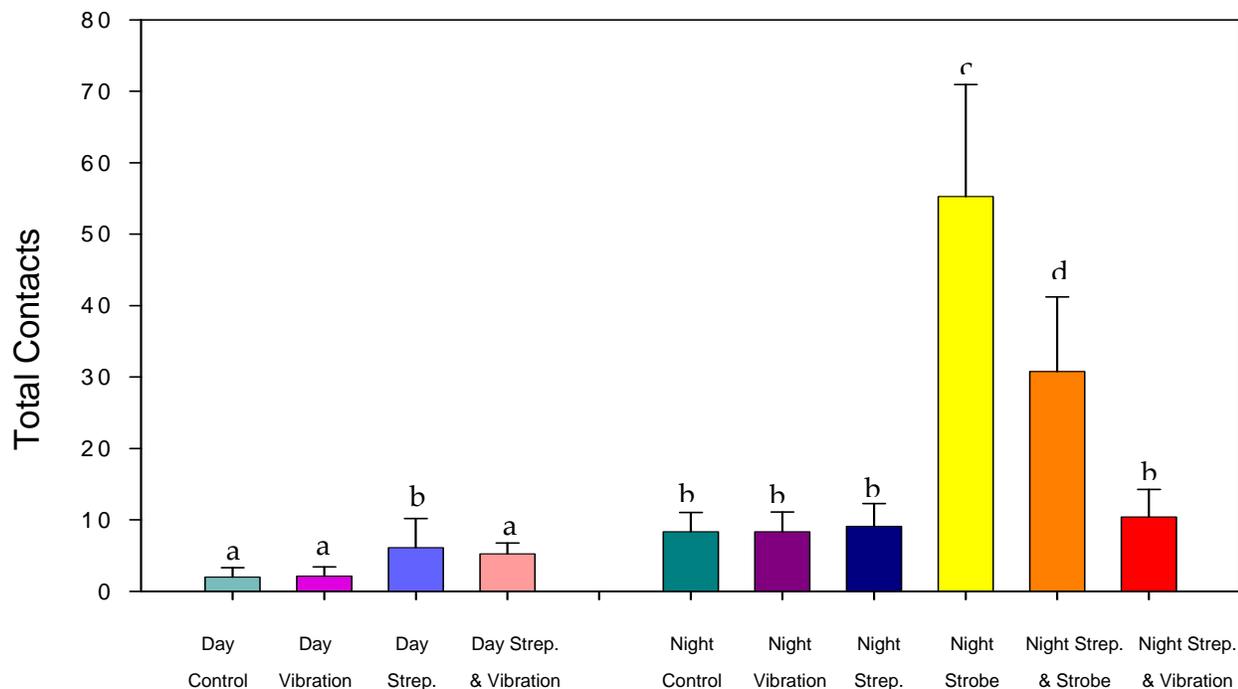
**Figure 10. Chinook trunk lateral line neuromasts treated with DASPEI at 5.0X magnification, showing a control fish that received no streptomycin treatment (left) and a fish that treated with a 24-h exposure to 0.5 g/l streptomycin (right).**

## **3.2. Results of the Swimming Trials**

Fish contacted the screens and louvers during all treatments and ANOVA tests found significant differences between treatments in every set of experiments at  $\alpha = 0.05$ . Significant differences were also found in the frequency that fish became permanently impinged on the screens or passed through the louvers between a couple treatments using Fisher's exact test. Significant results for each species are detailed below.

### **3.2.1. Steelhead**

The results for the steelhead swimming trials can be seen in Figure 11. The results were similar to the results from Cech and Mussen 2006 and therefore the data from the two sets of experiments was pooled with for analysis. During the daytime trials fish in the streptomycin treatments made significantly more contacts than the control treatments ( $p = 0.0036$ ). Fish in the nighttime treatments all made significantly more contacts than the daytime controls ( $p < 0.0001$ ). During the night the fish in the flashing strobe light treatment made significantly more contacts than the other treatments ( $p < 0.0001$ ). Very few steelhead became impinged during the experiments in any of the treatments, as shown in Table 1.



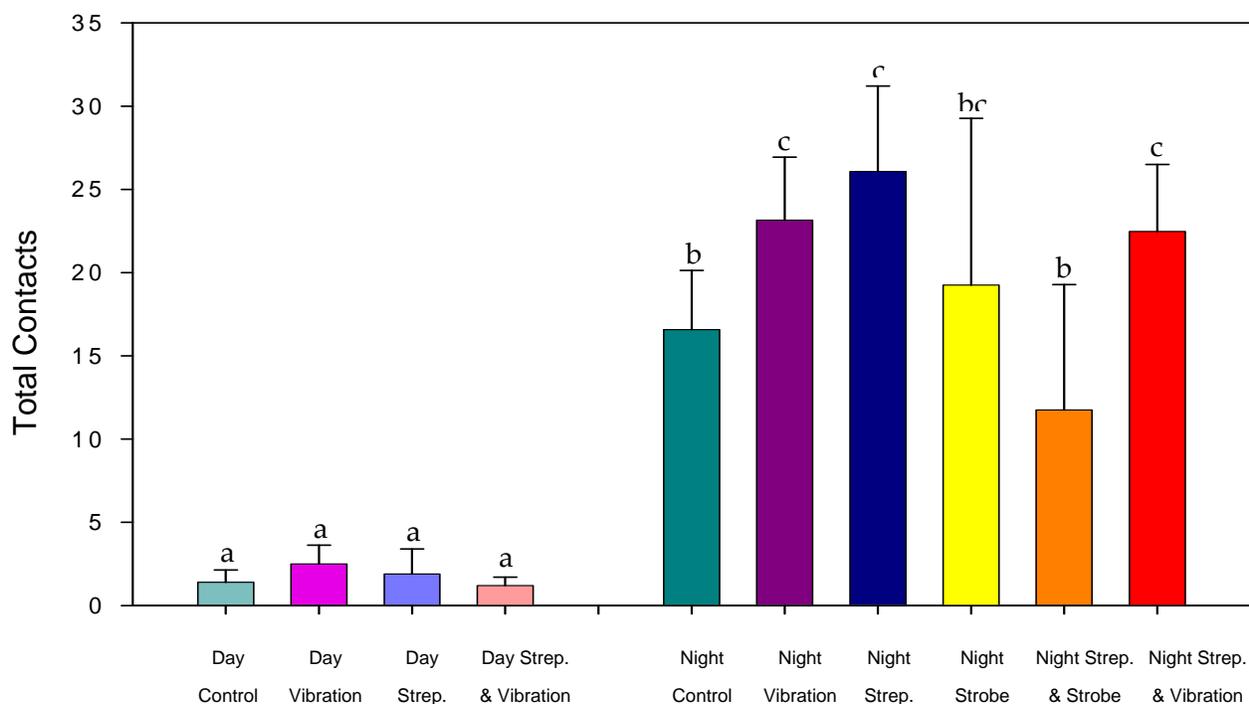
**Figure 11. Mean (+ SE) number of contacts steelhead made against the fish screen during 15-minute trials. Different letters indicate significantly different treatment groups. The data includes results from Cech and Mussen 2006.**

**Table 1. Numbers of fish tested and percentages that became permanently impinged on the screens or passed through the louvers in each treatment.**

SCREENS	shiner surfperch		staghorn sculpin		steelhead		splittail	
	sample size	impinged	sample size	impinged	sample size	impinged	sample size	impinged
Day Control	14	7%	5	0%	8	25%	10	0%
Day Vibration	-	-	-	-	8	0%	10	0%
Day Streptomycin	-	-	-	-	8	0%	10	0%
Day Strep.& Vibration	-	-	-	-	8	0%	10	0%
Night Control	14	7%	5	0%	12	0%	14	7%
Night Flash	13	15%	5	0%	4	0%	4	50%
Night Vibration	13	15%	5	0%	12	0%	14	36%
Night Streptomycin	13	8%	5	40%	12	8%	13	69%
Night Strep. & Vibration	-	-	-	-	12	0%	15	53%
Night Strep. & Flash	-	-	-	-	4	25%	4	75%

### 3.2.2. Splittail

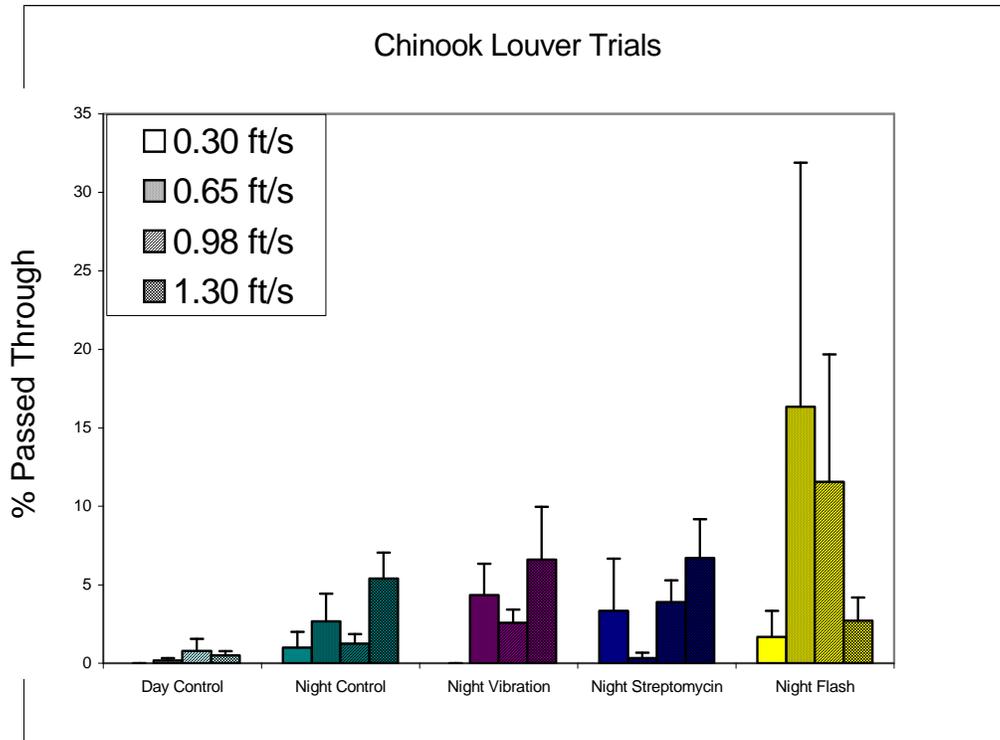
The results for the splittail swimming trials can be seen in Figure 12. The splittail made significantly more contacts against the screens at night than during the day ( $p < 0.0001$ ), but showed no significant differences among daytime treatments. Fish in the nighttime control treatment contacted the screens significantly less than fish in the nighttime streptomycin treatments ( $p < 0.0001$ ) and nighttime vibration treatments ( $p = 0.0070$ ). Also during the nighttime a significantly higher percent ( $p = 0.0010$ ) of the streptomycin-treated fish (69%) became permanently impinged on the screens compared to the control-treatment fish (7%) as seen in Table 1.



**Figure 12. Mean (+ SE) number of contacts splittail made against the fish screen during 15-minute trials. Different letters indicate significantly different treatment groups.**

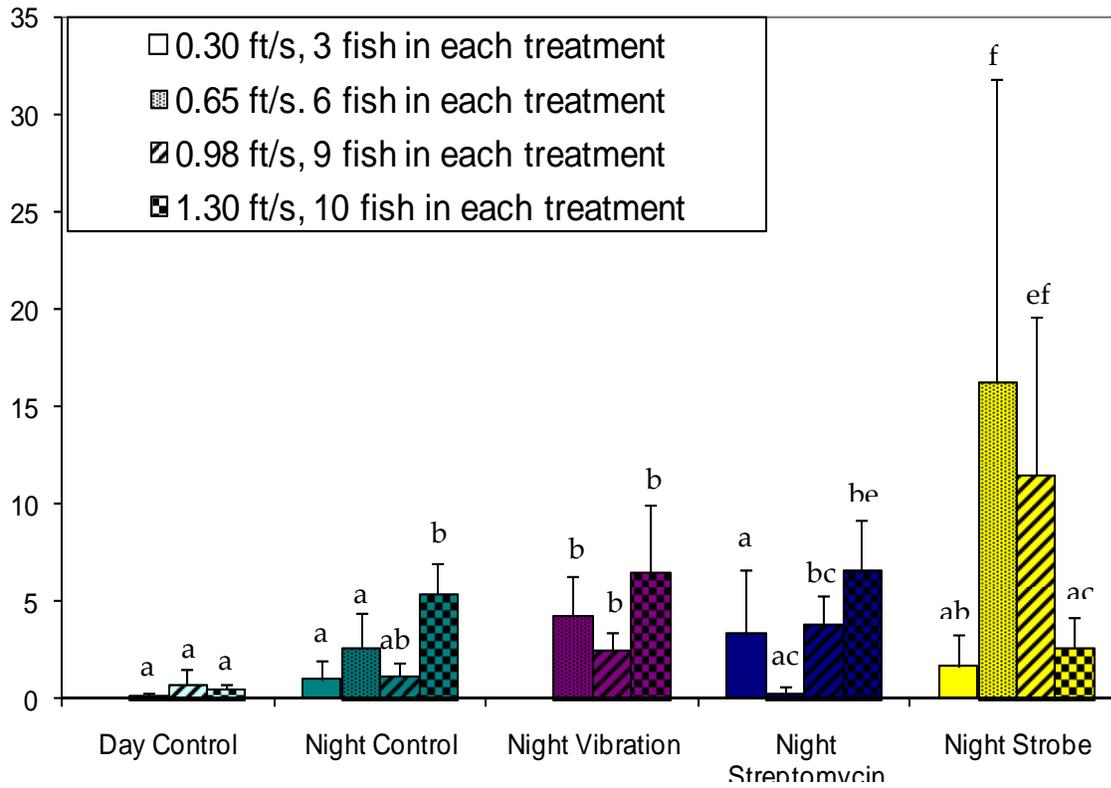
### 3.2.3. Chinook Salmon

The results for the Chinook salmon trials can be seen in Figure 13 and 14. At all velocities fish in the daytime control treatment made very few contacts and had few fish pass through the louvers. At the slowest water velocity tested (0.3 ft/s) no fish passed through the louvers and the fish made very few contacts with the louvers. In general the fish in the nighttime control, streptomycin and vibration treatment groups contacted the louvers more frequently and had a greater chance of passing through the louvers at higher velocities. In the strobe-light treatments the percentage of fish passing through the louvers also increased with water velocity, but the fish in this treatment had significantly more contacts at the middle water velocities of 0.56 ft/s and 0.98 ft/s.



**Figure 13. Percentage of Chinook salmon that passed through the louvers at 4 water velocities (0.3, 0.65, 0.98, & 1.30) in the 5 different treatments during 15 minute trials.**

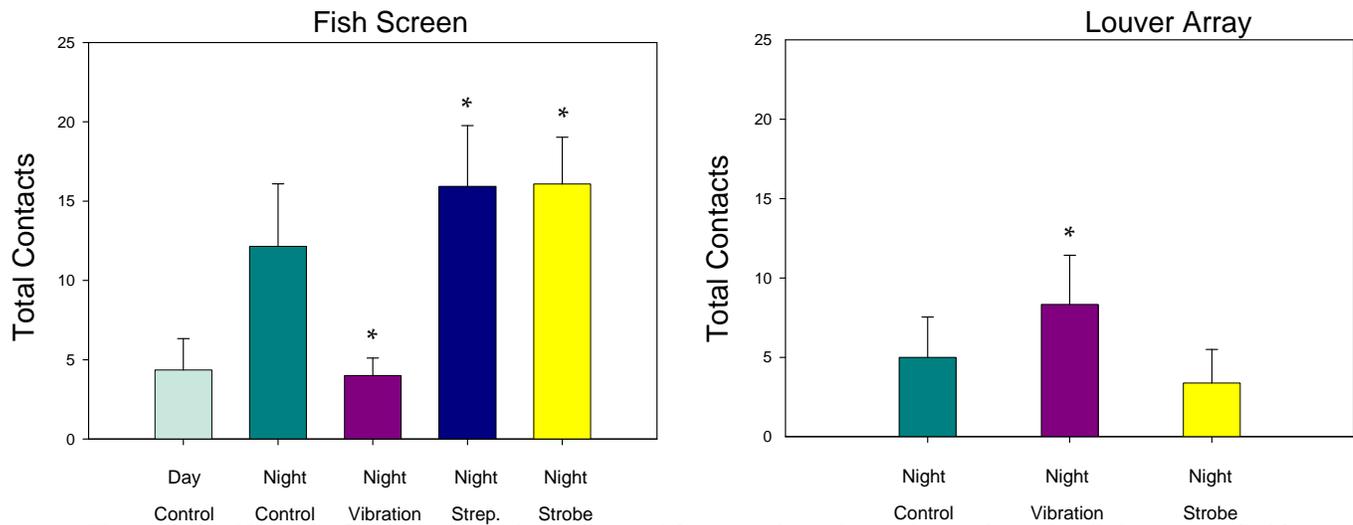
## Chinook Louver Trials



**Figure 14. Mean (+ SE) number of contacts Chinook salmon made against the louver during 15-minute trials. Letters indicate significantly different treatment groups**

### 3.2.4. *Shiner Surfperch*

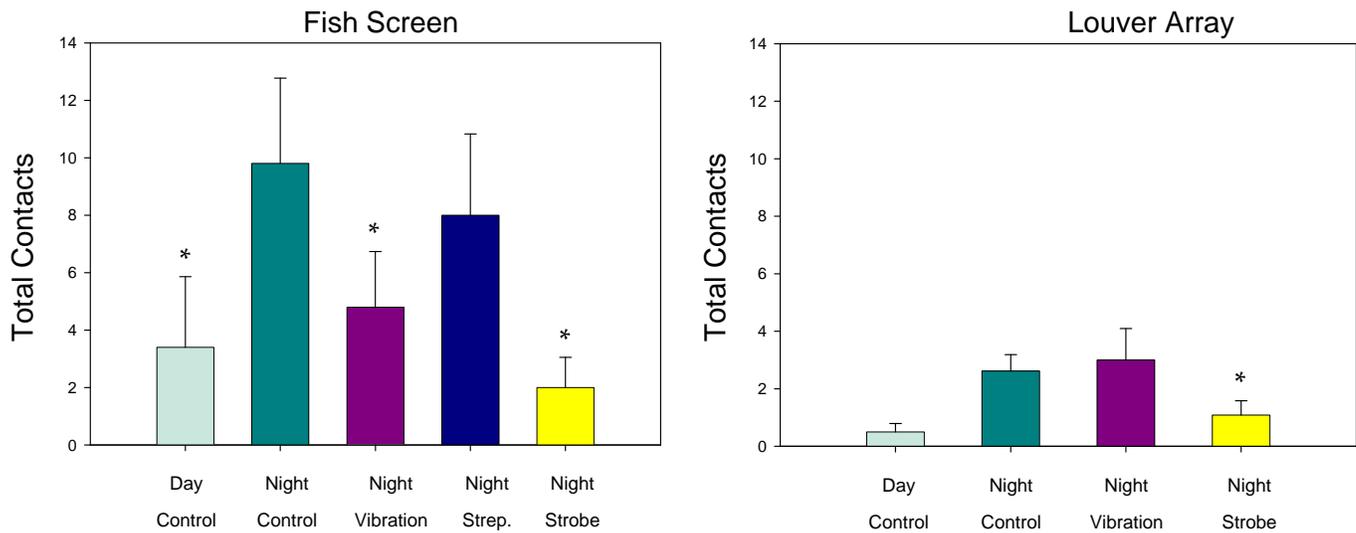
The results for the surfperch swimming trials can be seen in Figure 15. Fish in the nighttime control contacted the wedge-wire screen significantly more times compared to fish in the daytime control ( $p < 0.0001$ ) and the nighttime vibration treatments ( $p < 0.0001$ ). In the louver trials the opposite trend was seen, where fish in the nighttime control made significantly less contacts compared to the fish in the nighttime vibration treatment ( $p = 0.0480$ ).



**Figure 15. Mean (+ SE) number of contacts shiner surfperch made against the fish screen (left) and louver array (right) during 15-minute trials. Due to minimal numbers of collected fish and time limitations no streptomycin or daytime control treatments were used in the louver experiments. Treatments that are significantly different from the night control are marked with an (\*).**

### 3.2.5. Staghorn Sculpin

The results for the sculpin swimming trials can be seen in Figure 16. Fish in the nighttime control contacted the wedge-wire screen significantly more times compared to fish in the daytime control ( $p = 0.0074$ ), nighttime vibration treatments ( $p = 0.0350$ ) and nighttime strobe light ( $p = 0.0007$ ) treatments. In the louver trials fish in the nighttime control treatment made significantly more contacts than fish in the nighttime strobe light treatment ( $p = 0.0303$ ). Also during the louver trials a significantly ( $p = 0.041$ ) smaller percentage of sculpin in the nighttime strobe light treatment passed through the louvers compared to sculpin in the nighttime control. However these results become non-significant following a Bonferroni correction reducing  $\alpha$  to 0.025.



**Figure 16. Mean (+ SE) number of contacts staghorn sculpin made against the fish screen (left) and louver array (right) during 15-minute trials. Due to time limitations, no streptomycin treatments were used in the louver experiments. Treatments that are significantly different from the night control are marked with an (\*).**



## 4.0 Conclusions and Recommendations

### 4.1. Conclusions

On average the fish contacted the screens and louvers significantly less during the day than during the night. This is probably because the fish were able to use visual cues during the day to perceive the screen as threatening and avoid it. During the night fish were frequently observed drifting back toward a screen and then swimming just before they came in contact with it. This indicates either that the fish were able to detect the screen at night, through their lateral-line system or sensitive low-light vision, or that they had learned the screens' location by contacting it earlier in the trial and remembered its location. Fish contacted the screen and louvers in every treatment tested, indicating that if a barrier was not in place most of the fish tested would have been drawn through the simulated diversion.

In the fish-screen trials, very few fish in the daytime or nighttime control groups became impinged, showing that for the tested species at the tested velocities wedge-wire screens can make effective barriers for water diversions that potentially allow fish to escape entrainment. The effectiveness of wedge-wire fish screens and louver arrays can be compared by looking at the shiner surfperch and staghorn sculpin trials, which tested both fish excluders. Both species showed a much higher likelihood of passing through the louvers than becoming impinged on the screen, indicating that using screens to prevent fish passage may be desirable vs. louvers. This is also true when the steelhead screen studies are compared to the Chinook salmon louver trials. Because some fish did not pass through the louvers, louvers seem to be preferable vs. an open (un-screened/louvered) diversion, for fish protection, especially at slow flows (< 0.65 ft/s).

#### 4.1.1. Streptomycin Treatments

At an adequately high dose, streptomycin sulfate was found to destroy the majority of neuromasts for all tested species. It is unknown whether the equilibrium and acceleration sensing neuromasts in the fish's inner ear were affected by the streptomycin treatments. The increased number of screen contacts seen in the splittail and surfperch treated with streptomycin at night, show that the lateral-line system can be very important in detecting and avoiding screens for some species at night. The splittail treated with streptomycin also appeared to contact the screens harder at night than the control fish and swam away from the screens much faster after they contacted them with less-precise rheotaxis than the control fish. This behavior resulted in most of the streptomycin-treated splittail becoming permanently impinged on the screens, compared to just one fish in the nighttime control group. The streptomycin-treated steelhead also contacted the screens more frequently in the daytime trials than the control fish. The steelhead could see the screens during these trials so the increased number of contacts may be a result of less-precise movements near objects without a functioning lateral-line system. The hatchery-born and reared steelhead frequently swam near the screens and showed very minor responses after coming in contact with them during all of the daytime trials. The velocity in the flume may not have been fast enough to properly challenge the steelhead. Many fish treated with streptomycin in all of the trials did not become impinged on the screens during the nighttime, showing that fish are capable of swimming effectively in a current without any external visual or vibration guidance.

#### **4.1.2. Vibration Treatments**

The shiner surfperch and staghorn sculpin showed a significant decrease in contacts with the screen when it was receiving low frequency impacts from the vibrator (like a large hammer hitting the screen every 1.5 seconds). The fish would commonly burst-swim forward into the current and away from the screen when the vibrator struck at the start of the trials and would burst-swim forward after contacting the screen throughout the trial. Some of the fish swam as far away from the screen as possible at the start of their trial and stayed in that position for the rest of the trial. This behavior was seen occasionally from fish in all the treatment groups, but was noticeably more common for surfperch in the nighttime vibration group. These findings indicate that low-frequency, near-field vibrations can help repel some marine fish from swimming near screened diversions. The surfperch and sculpin showed less of a response to the vibrating-louver array. Most of the sculpin in the louver trials passed through the louvers at the very start of the experiment, so they had little time to be repelled. The surfperch in the vibrating louver trials swam in front of the louvers for a longer time, compared to that of the control group, before they passed through, and this resulted in an increased number of contacts. So although the surfperch contacted the louvers more when the louver was vibrating, it actually was repelling the fish temporarily.

The vibration treatments appeared to be mostly ignored by steelhead, splittail and Chinook salmon, although the splittail contacted the screens more frequently at night when the vibrators were running. Occasionally steelhead were seen slowly drifting back to a vibrating screen while swimming, resting against it without swimming for few seconds and then swimming off the screen and slowly away. Therefore it appears that the steelhead and splittail did not find the vibrations threatening. This may be because the vibrators used in the freshwater trials ran at faster frequencies (65Hz and 45Hz) than the target range of 10-15Hz, which is believed to repel fish. The vibrator used in the marine experiments was also somewhat out of the target range (running at only 0.75Hz). In the Chinook salmon louver trials at the end of the project a vibrator was located and tested that ran at a frequency of 11 Hz. The Chinook salmon still showed no strong response to it under the tested water velocities. It is possible that these fish would respond to a vibrator attached to the screen or louver in a vertical orientation to a greater extent than the horizontal orientation used in our trials.

#### **4.1.3. Strobe Light Treatments**

In the strobe-light treatments the staghorn sculpin actively swam away from the lighted screens and louvers shortly after coming to rest on them and sometimes before they made contact. In the strobe-light treatment, sculpin made fewer total contacts compared to the control fish, because they avoided swimming near the flashing screens and louvers. Also, fewer sculpin passed through the louvers while the strobe light was functioning. This was in strong contrast to the sculpin in the other treatments. Staghorn were not active swimmers and often adhered to the bottom of the chamber, non-swimming, by using their large pectoral fins as “diving planes” (i.e., negative-lift surfaces). In non-strobe light treatments the staghorn commonly rested near or on the screens, sometimes laying on them horizontally with their ventral side on the screen. The sculpin trials show that strobe lights can ward some fish species away from screens.

Steelhead, Chinook salmon, and shiner surfperch displayed the opposite reaction to the strobe lights and contacted the screens or louvers more frequently during the nighttime trials when the strobe lights were flashing compared to the control fish. The steelhead appeared to be confused and startled by the strobe lights. In the non-strobe-light nighttime treatments, steelhead would frequently swim in front of the screen contacting it occasionally for the first few minutes and then swim away from the screens to the front of the chamber. In the steelhead strobe-light treatments the fish made initial contact with the screen and then frequently burst-swam rapidly around the chamber, contacting the screens severely and repeatedly for the first few minutes. When the steelhead burst-swam away from the strobe lights they commonly contacted the front screen and then turned around and swam back into the wedge wire screens many times, indicating that they were unable to remove themselves from the stimulus. Also an interesting observation was that when the current was stopped in the flume, and the strobe light was turned on the steelhead would swim to the opposite side of the chamber and stay in that location for many minutes. During the Chinook salmon louver trials, the swimming area in front of the louvers was doubled to allow the fish more distance to retreat from the strobe lights, but like the steelhead they showed the greatest number of touches in the strobe-light treatments. The Chinook salmon appeared to swim faster and more frantically under the strobe lights and may need a much greater distance, or some type of velocity+light refuge for the strobe light to be effective. The surfperch appeared to swim near the screens more frequently while the strobe light was running, which may have caused their increased number of total contacts compared to the control.

## **4.2. Recommendations**

The experiments indicate that fish screens and louver arrays placed in front water diversions may allow fish to potentially escape entrainment. The marine fish responded similarly to freshwater species when encountering fish screens, showing that wedge-wire fish screens can be beneficial for some marine species. Fish avoided contact with screens and louvers to a greater extent during the day than night, which suggests that pumping should be reduced during the nighttime. The findings show that different fish species rely on both visual and mechanosensory cues, to different degrees, to detect and avoid physical barriers while swimming in a current. Vibrating devices that emit low-frequency, strong near-field vibrations may have potential at repelling fish, but further testing is needed before any general statements can be made. Strobe lights may also be an effective deterrent, but the fish must have a space to swim to, away from the flashes, to make them effective. Behavioral guidance devices directed at either sensory system can be effective at guiding fish away from hazards, but they may only be effective under certain conditions (e.g., nighttime) or for certain species. Installing screens to prevent fish passage may be desirable vs. louvers, but louvers are preferable for fish protection vs. an open (i.e., unscreened/louvered) diversion.

Another consideration is that these studies were tested in clean laboratory conditions, where the water was clear, no debris was present in the flumes, fouling the screens, and predators were absent. All of these factors are commonly found in natural settings near water intakes and are likely to affect a fish's swimming behaviors. The relative importance of these other factors should be determined prior to implementing any new screening technologies. Future laboratory studies could increase the turbidity of the water and, perhaps, cover portions of the

screen or louvers with debris to simulate natural settings. Also, large predators, such as striped bass (*Morone saxatilis*) could be introduced into larger-sized flumes to determine their effects on fish entrained near screens. Concurrent studies monitoring the behavior of fish near water intakes in natural settings would also be very useful to determine if the trends observed in the laboratory are present in the wild.

### **4.3. Benefits to California**

The results of this project can help to minimize potential impacts of water diversions on wild and hatchery fish populations. Fish screens are the current solution for protecting fish from numerous water diversions in California. Therefore, any increase in these screens' effectiveness should substantially assist California's fish populations and lessen the impacts of electric power generation and other practices that require water extractions. The findings from this project will help direct future research in designing an effective, close-proximity fish-screen deterrent.

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