

Stress Response and Avoidance Behavior of Fishes as Influenced by High-Frequency Strobe Lights

NATHAN S. RICHARDS*¹ AND STEVEN R. CHIPPS

U.S. Geological Survey, South Dakota Cooperative Fish and Wildlife Research Unit, Department of Wildlife and Fisheries Sciences, South Dakota State University, Brookings, South Dakota 57007, USA

MICHAEL L. BROWN

Northern Plains Biostress Laboratory, Department of Wildlife and Fisheries Sciences, South Dakota State University, 2140 B, Brookings, South Dakota 57007, USA

Abstract.—We examined the effects of strobe lights on plasma cortisol concentrations and avoidance behavior across a broad range of fish taxa. Representative fish taxa from five families were evaluated and included: Centrarchidae (largemouth bass *Micropterus salmoides*), Cyprinidae (fathead minnow *Pimephales promelas*), Ictaluridae (channel catfish *Ictalurus punctatus*), Percidae (yellow perch *Perca flavescens*), and Salmonidae (Chinook salmon *Oncorhynchus tshawytscha*). Mean (\pm SE) plasma cortisol concentrations for channel catfish (89 ± 22 ng/mL), yellow perch (81 ± 39 ng/mL), and Chinook salmon (173 ± 27 ng/mL) increased significantly compared with those in control groups (50 ± 11 , 3.0 ± 1.9 , and 102 ± 35 ng/mL, respectively) after 1 h of exposure to strobe lights. After 7 h of exposure, plasma cortisol levels were similar to those in control groups for all fish taxa. Fathead minnow showed no detectable response to strobe lights at either 1 or 7 h of exposure. Behavior experiments showed that the mean distance moved from the strobe light varied significantly between test and control fish and was highest for largemouth bass (mean distance after 1 h = 8.3 m), followed by Chinook salmon (7.3), yellow perch (7.3), and channel catfish (5.1). In contrast, avoidance behavior by fathead minnow exposed to strobe lights did not differ from that of controls. Although a significant increase in plasma cortisol level was useful for predicting an avoidance response, relative change in cortisol concentration was a poor indicator of sensitivity of individual fish taxa to strobe lights. Direct observations of avoidance behavior revealed that largemouth bass, Chinook salmon, and yellow perch were more sensitive to strobe lights than channel catfish and fathead minnow. Lack of both a cortisol response and avoidance behavior by fathead minnow indicates low sensitivity of this species to strobe lights and warrants further investigation into the effectiveness of strobe lights on cyprinids.

Fish deterrent systems are routinely used in management applications to help guide fish away from potential barriers or sources of mortality (e.g., hydropower turbines; Adams et al. 2001; Konigson et al. 2002). A variety of fish deterrent technologies have been developed that include underwater lights (Patrick et al. 1985; Sager et al. 1987; Konigson et al. 2002), high- and low-frequency sounds (Goetz et al. 2001; Mueller et al. 2001; Sand et al. 2001), bubble curtains (Patrick et al. 1985; Welton et al. 2002), electric stimuli (Popper and Carlson 1998; Patrick et al. 1985), and combinations thereof.

Strobe lights are the most widely used underwater light system and have been successful in altering the behavior of fishes (Popper and Carlson 1998; Bullen and Carlson 2003). Nemeth and Anderson (1992) evaluated effects of strobe lights on juvenile coho

salmon *Oncorhynchus kisutch* under controlled conditions and found that smolts typically hid when subjected to lights. Similarly, Maiolie et al. (2001) reported an 80% reduction in density of kokanee *O. nerka* within a 30-m radius when the fish were subjected to strobe lights in the field. In addition, strobe lights elicited strong avoidance behaviors in Chinook salmon *O. tshawytscha* and yearling coho salmon held in experimental cages (Amaral et al. 2001; Ploskey and Johnson 2001).

Factors such as species, life stage, physiological state, and environmental conditions may influence the effectiveness of strobe lights and have important implications in the application of strobe light technology (Anderson 1988; Feist and Anderson 1991; Nemeth and Anderson 1992; Popper and Carlson 1998). Although effective in altering the behavior of fishes, little is known about the relative sensitivity of different fish taxa to underwater strobe lights. Indeed, results for individual species are often variable owing to different experimental settings, environmental conditions, or light sources (Popper and Carlson 1998; Konigson et al. 2002; Bullen and Carlson 2003).

* Corresponding author: Nathan.Richards@state.sd.us

¹ Present address: U.S. Fish and Wildlife Service, 9053 Route 148, Suite A, Marion, Illinois 62959, USA.

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In this study, we evaluated the effects of strobe lights on the plasma cortisol response (as an indicator of stress) and avoidance behavior across a broad range of fish taxa exposed to similar environmental conditions. We discuss the implications of stress and behavioral responses across taxa and highlight the sensitivity of individual species to strobe light exposure.

Methods

Fish taxa.—To evaluate fish sensitivity to strobe lights, we quantified plasma cortisol concentrations and avoidance behaviors of representative species from five different families: Cyprinidae, Centrarchidae, Percidae, Ictaluridae, and Salmonidae. Native fathead minnow *Pimephales promelas* ($N = 400$) were provided by a local bait dealer (Porter's Bait Farm, Brookings County, South Dakota). Channel catfish *Ictalurus punctatus* ($N = 120$), yellow perch *Perca flavescens* ($N = 118$), and largemouth bass *Micropterus salmoides* ($N = 119$) were obtained from a licensed aquaculture facility (ButterFlake Aquafarm, Brookings County). Chinook salmon ($N = 102$) were provided by McNenny State Fish Hatchery (South Dakota Department of Game, Fish, and Parks [SDGFP]). Fish were transported to South Dakota State University in a 2.2-m³ hauling tank and were slowly (2–3 h) acclimated to laboratory conditions by mixing water from our laboratory recirculating system with water from the transport tank. Fish were then added to a 1,500-L recirculating tank and maintained for 4–6 d before the experiments. Any dead, sick, or lethargic fish were removed from the tank daily using small dip nets maintained in disinfectant. However, losses were minimal and all experimental fish were deemed healthy at the onset of the experiments. The recirculating system was drained and disinfected at the end of each set of experiments; it was re-filled, aerated to degas chlorine, and allowed to condition for 1–2 weeks before the next group of fish was obtained. Because fish were held for less than 1 week, we experienced no problems with disease outbreaks and did not have to treat fish with any antibiotics.

Mean daily water temperatures in the holding tank ranged from 14°C to 24°C depending on the month (July–September) in which fish were obtained; warm-water fishes (e.g., centrarchids and ictalurids) were tested at temperatures ranging from 21°C to 24°C, whereas coolwater taxa (salmonids) were tested at temperatures from 14°C to 15°C. All species were evaluated separately.

Stress response.—We used six 900-L circular tanks to evaluate effects of strobe lights on plasma cortisol response in fishes. Three tanks were used as controls (no light), and three tanks were each outfitted with two

TABLE 1.—Mean (SE) size of fish species used to evaluate effects of underwater strobe lights on plasma cortisol concentration. Mean total length (TL) and weight (mass) are given for each taxon ($n = 20$ fish/species) along with the range of water temperatures in experimental tanks.

Species	Mean TL (mm)	Mean mass (g)	Water temperature (°C)
Fathead minnow	50 (0.82)	1.1 (0.06)	21.1–21.8
Channel catfish	147 (2.15)	17 (0.78)	22.3–23.1
Yellow perch	134 (1.74)	25 (1.17)	22.9–24.0
Largemouth bass	224 (4.10)	145 (12.26)	23.2–24.1
Chinook salmon	178 (3.56)	49 (3.65)	14.0–14.8

cylindrical strobe lights (0.16 m in length \times 0.04 m in diameter), each with a flash rate of 86 flashes/min (Diversitronics, Inc., Elmhurst, Illinois). Strobe lights were installed into a clear plastic tube (0.50 m in length \times 0.16 m in diameter) submersed 0.3 m below the water surface. All tanks were covered with black polyethylene plastic to preclude light transmission from the tank. Two trials were conducted for each species for a total of six replicates per treatment.

At the start of each trial, fish were netted from the holding tank and randomly stocked in either a treatment (strobe light) or control tank. We reduced the risk of using any pre-stressed fish in the experiments by removing lethargic or slow-moving fish from the holding tank. In trials with fathead minnow, 18 fish were added to each of the 6 tanks. In trials with channel catfish, yellow perch, largemouth bass, or Chinook salmon, four fish were added to each tank (Table 1). More fathead minnow were used to ensure that a sufficient blood sample (>100 μ g pooled) was collected for analysis of plasma cortisol. Fish were allowed to acclimate to the circular tanks for at least 24 h before the experiments began.

We conducted all experiments in the dark from 2000 to 0600 hours. Strobe lights were turned on and allowed to run for 1 h, after which two to three individuals were randomly netted from each control and treatment tank for blood collection. Fish were handled quickly after being netted from the tanks (<5 s) and anesthetized with a nonlethal concentration of tricaine methanesulfonate (MS-222). Blood was withdrawn from caudal vessels after severing the caudal peduncle and was collected in hematocrit tubes for fathead minnow ($n = 3$ fish/tank) or 2-mL heparinized vials for all other species ($n = 2$ fish/tank). Fish remaining in the tanks were exposed to an additional 6 h of darkness (control) or strobe lights (treatment), and the same procedure was used to obtain blood samples after a total of 7 h. Samples were centrifuged at 3,500 revolutions/min for 12 min, and

TABLE 2.—Mean size (SE) of fish species used to evaluate effects of underwater strobe lights on avoidance behavior in raceway tank experiments. Mean total length (TL) and weight (mass) are given for each taxon ($n = 20$ fish/species) along with the range of water temperatures in experimental tanks.

Species	Mean TL (mm)	Mean mass (g)	Water temperature (°C)
Fathead minnow	52 (0.83)	1.3 (0.08)	22.5–23.2
Channel catfish	160 (2.06)	24 (1.10)	22.6–23.3
Yellow perch	128 (1.28)	19 (0.79)	23.6–24.7
Largemouth bass	219 (4.24)	130 (10.49)	21.3–21.9
Chinook salmon	201 (5.01)	75 (6.68)	17.4–18.1

plasma was extracted and stored at -80°C pending analysis.

Plasma cortisol concentration (ng/mL) was determined by radioimmunoassay (Farmer and Pierce 1974; Foster and Dunn 1974). Values were \log_{10} transformed to normalize the residuals before analysis, and we tested the hypothesis that cortisol concentration was higher in fish exposed to strobe lights than for fish not exposed to light (one-tailed t -test; SAS Institute 1999).

Avoidance behavior.—We evaluated avoidance behavior for each fish species in an experimental raceway (9.2×0.7 m; 0.6 m deep). Tests were conducted under static (no flow) conditions at a water depth of 0.5 m and water temperatures of 17 – 24°C depending on species (Table 2). Four strobe lights (86 flashes/min; Diversitronics) were installed at one end of the raceway by placing lights into a submersed clear plastic tube (0.50×0.16 m). Sides of the experimental tank were marked at 15-cm intervals, and four video cameras were mounted 3 m above the tank, each filming one of four sections of the tank.

Fish were added to the raceway and allowed to acclimate for at least 12 h before the experiments began. For each trial, we used either fathead minnow ($n = 20$), channel catfish ($n = 10$), yellow perch ($n = 10$), largemouth bass ($n = 10$), or Chinook salmon ($n = 6$; Table 2). Because of low availability, only six Chinook salmon were used in each trial.

A total of three trials were conducted for each species; naïve fish were used in each trial. A trial consisted of paired control (strobe lights off) and treatment (strobe lights on) groups. Video cameras were turned on while fish were being maintained in the dark. After 2 min of darkness, overhead lighting was turned on for approximately 10 s and each fish location was recorded at the instant the lights were turned on. Overhead lights were then turned off, and fish were maintained in darkness for an additional 60 min, after which the lights were turned on and fish locations were again recorded by the video cameras. Fish were then allowed to acclimate in darkness for 30

min before the strobe lights were turned on. To assess effects of strobe lights on fish behavior, similar protocols were used to document fish locations in the tank. Strobe lights were turned on at the beginning of a trial; after 2 and 60 min of strobe light exposure, fish locations were determined by freezing and recording the video image immediately after the overhead lights were turned on.

We measured the horizontal distance of each fish from the strobe light location based on video coverage of control (no light) and strobe-light-exposed fish. A paired t -test was used to evaluate the hypothesis that mean displacement away from the light source was greater for exposed fish than for controls (i.e., strobe light minus control > 0 ; $\alpha = 0.10$). To assess relative sensitivity across taxa, we also used analysis of variance to compare mean displacement from the light source after 1 h of strobe light exposure. Duncan's multiple-range test was then used to evaluate significant differences ($\alpha = 0.10$) in avoidance behavior among species.

To assess the relationship between cortisol response and behavior, we calculated the relative change in cortisol concentration for each taxon as the difference in mean cortisol concentration after 1 h of exposure between exposed fish and control fish. We then evaluated the relationship between mean displacement from the strobe light after 1 h (behavior experiments) and relative change in cortisol concentration using Spearman's rank correlation analysis.

Results

Stress Response

Plasma cortisol concentrations were significantly higher in channel catfish ($t = 2.22$, $P = 0.02$), yellow perch ($t = 3.94$, $P = 0.005$), and Chinook salmon ($t = 1.91$, $P = 0.03$) exposed to strobe lights for 1 h than in control fish (Table 3). Mean plasma cortisol concentration in largemouth bass after 1 h of strobe light exposure was not significantly different from that of controls. Similarly, we found no evidence that strobe lights elicited a cortisol response in fathead minnow after 1 h of exposure (Table 3). After 7 h of strobe light exposure, plasma cortisol concentrations were similar between exposed and control groups ($P > 0.05$; Table 3). Moreover, patterns in cortisol concentration were similar for fathead minnow after 1 and 7 h of strobe light exposure.

Behavior Experiments

Chinook salmon, largemouth bass, and yellow perch moved a significant distance away from the light source after 2 min of strobe light illumination (Figure 1). For channel catfish, mean (\pm SE) distance from the

TABLE 3.—Mean plasma cortisol concentration (ng/mL) for control fish and test fish after 1 and 7 h of exposure to underwater strobe lights. Mean values followed by differing letters indicate a significant increase in plasma cortisol for that exposure period based on one-tailed *t*-tests ($P < 0.05$).

Species	1-h cortisol		7-h cortisol	
	Control ($n = 6$)	Test ($n = 6$)	Control ($n = 6$)	Test ($n = 6$)
Fathead minnow	147.9 (18.1) z	99.8 (12.2) z	153.4 (12.2)	97.5 (10.3)
Channel catfish	50.0 (13.1) z	89.7 (14.2) y	79.4 (6.2)	84.7 (12.6)
Yellow perch	2.8 (1.2) z	81.7 (36.0) y	51.9 (34.5)	63.1 (19.9)
Largemouth bass	85.2 (16.2) z	96.6 (14.9) z	164.1 (20.7)	140.4 (21.6)
Chinook salmon	102.1 (31.3) z	173.2 (25.1) y	100.4 (21.9)	110.7 (24.5)

strobe lights was not significantly different between exposed fish (5.95 ± 0.44 m; $n = 3$) and controls after 2 min (4.54 ± 0.58 m; $n = 3$). After 60 min of strobe light illumination, Chinook salmon, largemouth bass, yellow perch, and channel catfish had moved farther from the light source than fish in control trials ($P < 0.10$; Figure 1). In contrast, strobe lights had little influence on distribution of fathead minnow after 2 and

60 min of illumination; we found no evidence that fathead minnow were displaced by strobe lights in the experimental raceway (Figure 1). Moreover, relative change in cortisol concentration was not related to mean distance moved from the light source ($n = 5$; Spearman's $\rho = 0.35$, $P = 0.55$). Comparisons among taxa revealed that mean distance from the light source was significantly higher for largemouth bass, Chinook salmon, and yellow perch than for channel catfish or fathead minnow (Duncan's multiple-range test: $n = 5$, $P < 0.05$).

Discussion

Plasma cortisol concentrations observed in our study were generally within the range reported for stress-elevated values of most teleost fishes (30–300 ng/mL; Barton et al. 2002). In a study of yellow perch exposed to handling stress, pre-stress and 1-h poststress plasma cortisol concentrations were 3.4 and 85 ng/mL, respectively (Barton et al. 2002), similar to the values we observed for control (2.8 ng/mL) and 1-h-exposed yellow perch (81.7 ng/mL). Moreover, elevated cortisol levels (or lack thereof) for Chinook salmon, yellow perch, channel catfish, and fathead minnow were congruent with observed behavioral responses to strobe lights after 1 h of exposure. In taxa exhibiting significant increases in plasma cortisol concentration with exposure to strobe lights, we observed significant changes in avoidance behavior. Conversely, we found no evidence of either increased cortisol level or change in behavior for exposed fathead minnow, implying that this species has low sensitivity to strobe lights (Richards 2006).

We found no significant changes in plasma cortisol concentration for strobe-light-exposed largemouth bass relative to control fish. Lack of a significant cortisol response may be due to the variable nature of cortisol measurements (Carmichael et al. 1984). Indeed, the timing of the peak poststress cortisol concentration may have varied across taxa and it is possible that our 1-h sampling interval did not capture such variation. In

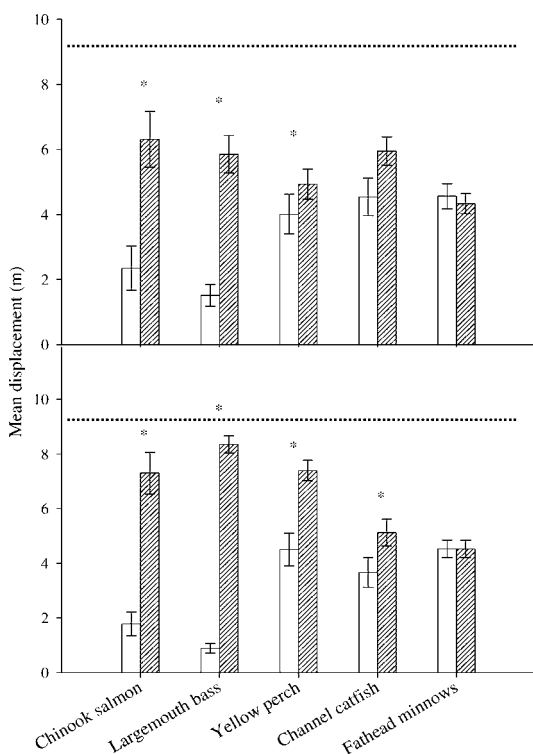


FIGURE 1.—Mean (\pm SE) displacement (m; distance from strobe lights) for control fish (open bars) and strobe-light-exposed fish (hatched bars) after 2 min (top panel) and 60 min (bottom panel) of strobe light illumination in an experimental raceway. Asterisks denote significant differences in mean displacement (paired *t*-test: $P < 0.10$). Horizontal lines indicate the maximum raceway length.

largemouth bass, cortisol concentration may have peaked after 1 h; if so, the values we measured would be lower than the maximum (Davis and Schreck 2005; A. Haukenes, University of Arkansas, personal communication). In addition, it may have been difficult to detect statistical differences because of confounding size effects. For example, largemouth bass were larger than other fishes used in the experiments. Therefore, stress levels due to confinement may have induced a greater stress response in largemouth bass than in smaller fish. Nonetheless, behavior experiments showed that largemouth bass avoided strobe lights, implying that the lack of a cortisol-related stress response between two time periods does not necessarily indicate that fish (e.g., largemouth bass) are insensitive to underwater light.

In our view, the relative sensitivity of fishes to strobe lights was better indexed by behavioral responses in the raceway experiments that would be more applicable to field settings. Standardized measures of variation (coefficient of variation) showed that cortisol concentrations were considerably more variable (48–36%) than avoidance responses (mean distance from strobe light = (36–57%), supporting the use of avoidance behavior as an index of sensitivity.

Fathead minnow did not exhibit a cortisol or avoidance response when exposed to strobe lights. Although not tested, high plasma cortisol levels were observed in fathead minnow maintained in the control tanks. It is unclear why cortisol levels were high in control fish as compared with test fish; one hypothesis may be that cortisol levels increase in fathead minnow when they are maintained in complete darkness. Because control tanks were covered by black plastic, they contained no ambient light that might normally be present at night (e.g., moonlight). As a gregarious shoaling species, fathead minnow may become disoriented in complete darkness, which thus may contribute to elevated cortisol levels. The Cyprinidae family includes a broad range of fish species that, in general, have not been evaluated in their responses to strobe lights. The lack of both a cortisol and behavioral response by fathead minnow warrants further investigation into the effectiveness of strobe lights on cyprinid species.

Acclimation to strobe lights by fishes is not well documented in the literature but would have important implications for the effectiveness of strobe light applications. After 7 h of strobe light exposure, we found no evidence (for any taxa) that plasma cortisol levels were higher in exposed fish than in controls. Fish may have become acclimated to strobe lights after prolonged periods of strobe light illumination; alternatively, confounding factors such as confinement stress

may have prevented us from detecting differences after 7 h. Cortisol levels in channel catfish, yellow perch, and largemouth bass, for example, increased in control tanks from 1 to 7 h. Although we have no clear explanation for this, it could be related to additive effects of confinement stress in the tanks, making it difficult to infer whether fish were acclimating to strobe lights after 7 h. Our behavioral experiments lasted only 1 h, so we were unable to test hypotheses about long-term (days to weeks) acclimation and how this would affect avoidance behavior. Further tests are needed to determine habituation effects for longer periods.

Several studies have indicated that strobe lights may attract some species (Brett and McKinnon 1953; Feist and Anderson 1991; Johnson et al. 2003). Although we did not observe attraction-type behavior in our 1-h experiments, Johnson et al. (2003) noted that the number of fish increased as the distance to the lights decreased, but fish near the lights exhibited an avoidance response. They postulated that light may attract invertebrate prey species to peripheral regions surrounding the lights, thereby increasing nighttime foraging efficiency for visually foraging fishes.

Tests of strobe lights under controlled conditions provided insight into the relative sensitivity of different fish taxa to strobe light illumination. Our findings suggested that ictalurids and cyprinids were less sensitive to underwater lights than other fish taxa. In field settings, however, variable environmental conditions may influence the magnitude of behavioral responses in fishes. Factors such as acclimation, prey attraction, water velocity, and turbidity are known to affect the efficacy of strobe light application and warrant further investigation, pending large-scale field applications.

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